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March 3, 1849

Safe Disposal of Radionuclides in Low-Level Radioactive-Waste Repository Sites: Low-Level Radioactive-Waste Disposal Workshop, U.S. Geological Survey, July 11–16, 1987, Big Bear Lake, Calif., Proceedings

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PARTICIPANTS

U.S. Geological Survey Workshop on
Low-Level Radioactive-Waste Disposal
Big Bear Lake, California,
July 11–16, 1987

Ruben Alvarado, Texas Low-Level Radioactive Waste Disposal Authority, Austin, Texas
Brian Andraski, U.S. Geological Survey, Carson City, Nevada
Marion S. Bedinger, U.S. Geological Survey, Denver, Colorado
Robert Blickwedehl, Dames and Moore, West Valley, New York
Edward R. Burt, North Carolina Geological Survey, Raleigh, North Carolina
Kevin F. Dennehy, U.S. Geological Survey, Columbia, South Carolina
Peter M. deVries, U.S. Geological Survey, Urbana, Illinois
George A. Dinwiddie, U.S. Geological Survey, Reston, Virginia
Joe DiLugosz, U.S. Environmental Protection Agency, Carson City, Nevada
Leo F. Emmett, U.S. Geological Survey, Rolla, Missouri
Jeffery M. Fischer, U.S. Geological Survey, Carson City, Nevada
Mark Fuhrmann, Nuclear Waste Research Group, Brookhaven National Laboratory, Upton, New York
Ronald Gaynor, U.S. Ecology, Newport Beach, California
Daniel J. Goode, U.S. Geological Survey, Reston, Virginia
John R. Gray, U.S. Geological Survey, Tucson, Arizona
Greg Hamer, Harding Lawson Associates, Tustin, California
Thomas E. Hakonson, Los Alamos National Laboratory, Los Alamos, New Mexico
Richard W. Healy, U.S. Geological Survey, Denver, Colorado
Scott T. Hinschberger, Low-Level Waste Programs, U.S. Department of Energy, Idaho Falls, Idaho
William F. Horak, U.S. Geological Survey, Oklahoma City, Oklahoma
Cheng-Yeng Hung, U.S. Environmental Protection Agency, Washington, D.C.
Vernon T. Ichimura, Chem-Nuclear Systems, Inc., Barnwell, South Carolina
Kenneth S. Johnson, Oklahoma Geological Survey, Norman, Oklahoma
Ruben Junkert, Department of Health Services, Sacramento, California
Kenneth L. Kipp, U.S. Geological Survey, Denver, Colorado
Michael J. Kleschulte, U.S. Geological Survey, Rolla Missouri
Charles Kreitler, Texas Bureau of Economic Geology, Austin, Texas
Maxine LaBranche, U.S. Geological Survey, Reston, Virginia
Edward R. Landa, U.S. Geological Survey, Reston, Virginia
Eric G. Lappala, Harding Lawson Associates, Novato, California
Barney D. Lewis, U.S. Geological Survey, Idaho Falls, Idaho
Mark A. Lyverse, U.S. Geological Survey, Louisville, Kentucky
Larry J. Mann, U.S. Geological Survey, Idaho Falls, Idaho
Peter B. McMahon, U.S. Geological Survey, Columbia, South Carolina
G. Lewis Meyer, Great Falls, Virginia
Patrick C. Mills, U.S. Geological Survey, Urbana, Illinois
James R. Nicholas, U.S. Geological Survey, Urbana, Illinois
W. David Nichols, U.S. Geological Survey, Carson City, Nevada
Gary R. Olhoeft, U.S. Geological Survey, Denver, Colorado
Myles D. Overton, U.S. Geological Survey, Oklahoma City, Oklahoma
Frederick L. Paillet, U.S. Geological Survey, Denver, Colorado
David E. Prudic, U.S. Geological Survey, Carson City, Nevada
Allan D. Randall, U.S. Geological Survey, Albany, New York
Joe E. Reed, U.S. Geological Survey, Denver, Colorado
Brent Russell, EG&G Idaho, Idaho Falls, Idaho
William F. Schwarz, New York State Energy Research and Development Authority, Albany, New York
Peter R. Stevens, U.S. Geological Survey, Reston, Virginia
Robert G. Striegl, Jr., U.S. Geological Survey, Urbana, Illinois
Warren E. Teasdale, U.S. Geological Survey, Denver, Colorado
Donald C. Thorstenson, U.S. Geological Survey, Reston, Virginia
David A. Webster, U.S. Geological Survey, Knoxville, Tennessee
Edwin P. Weeks, U.S. Geological Survey, Denver, Colorado
Michael F. Weber, U.S. Nuclear Regulatory Commission, Washington, D.C.
Donald Womeldorf, California Department of Health Services, Sacramento, California

Safe Disposal of Radionuclides in Low-Level Radioactive-Waste Repository Sites: Low-Level Radioactive-Waste Disposal Workshop, U.S. Geological Survey, July 11–16, 1987, Big Bear Lake, Calif., Proceedings

Edited by MARION S. BEDINGER and PETER R. STEVENS

Hydrologic studies of the performance of existing low-level radioactive repository sites in the United States provide lessons that can be used to guide siting and design of future low-level radioactive waste repositories

U.S. GEOLOGICAL SURVEY CIRCULAR 1036

DEPARTMENT OF THE INTERIOR
MANUEL LUJAN, Jr., Secretary

U.S. GEOLOGICAL SURVEY
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March 3, 1849

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CONVERSION FACTORS

For the use of those readers who may prefer to use inch-pound units rather than International System (SI) units, the conversion factors for the terms used in this report are listed below.

Multiply metric unit	By	To obtain inch-pound unit
pascal	1×10^{-5}	bar
becquerel (Bq)	0.027027	curie
cubic meter (m^3)	35.31	cubic foot
gram (g)	0.03527	ounce
hectare (ha)	2.471	acre
liter (L)	33.82	ounce, fluid
meter (m)	3.281	foot
metric ton (t)	1.102	short ton
square centimeter (cm^2)	0.1150	square inch
square kilometer (km^2)	0.3861	square mile
square meter (m^2)	10.7643	square foot

SI PREFIXES

Factor by which unit is multiplied	Prefix	Symbol
10^3	kilo	k
10^2	hecto	h
10	deka	da
10^{-1}	deci	d
10^{-2}	centi	c
10^{-3}	milli	m
10^{-6}	micro	μ
10^{-9}	nano	n
10^{-12}	pico	p

Convert degree Celsius (°C) to degree Fahrenheit (°F) by using the formula:

$$°F=1.8\times°C+32$$

Sea level: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929—a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Safe Disposal of Radionuclides in Low-Level Radioactive-Waste Repository Sites: Low-Level Radioactive-Waste Disposal Workshop, U.S. Geological Survey, July 11–16, 1987, Big Bear Lake, Calif., Proceedings

Marion S. Bedinger *and* Peter R. Stevens, *editors*

INTRODUCTION

In the United States, low-level radioactive waste is disposed by shallow-land burial. Low-level radioactive waste generated by non–Federal facilities has been buried at six commercially operated sites; low-level radioactive waste generated by Federal facilities has been buried at eight major and several minor Federally operated sites (fig. 1). Generally, low-level radioactive waste is somewhat imprecisely defined as waste that does not fit the definition of high-level radioactive waste and does not exceed 100 nCi/g in the concentration of transuranic elements. Most low-level radioactive waste generated by non–Federal facilities is generated at nuclear powerplants; the remainder is generated primarily at research laboratories, hospitals, industrial facilities, and universities. On the basis of half lives and concentrations of radionuclides in low-level radioactive waste, the hazard associated with burial of such waste generally lasts for about 500 years. Studies made at several of the commercially and Federally operated low-level radioactive-waste repository sites indicate that some of these sites have not provided containment of waste nor the expected protection of the environment.

This volume contains papers presented at the U.S. Geological Survey Workshop on Low-Level Radioactive-Waste Disposal that was held at Big Bear Lake, California, July 11–16, 1987. Participants at the meeting included geoscientists of the U.S. Geological Survey who are engaged in onsite investigations of low-level radioactive-waste repository sites; scientists of National laboratories, States, and private industry who are working on problems of radioactive-waste disposal; and scientists from the U.S. Nuclear Regulatory Commission, the U.S. Environmental Protection Agency, and the U.S. Department of Energy who are concerned with disposal of low-level radioactive waste. The purpose of the workshop was to address specific broad questions concerning the safe disposal of low-level radioactive waste.

The topics posed for principal consideration by the participants were as follows:

1. *Hydrologic conditions at existing repository sites.* Engineering practices at low-level radioactive-waste repository sites greatly affect the local geohydrology, the stability of the waste trenches, and consequently the efficiency of the repository site to contain the waste. Furthermore, the natural geohydrology of the repository site greatly affects the proper engineering design and construction of the site. Papers presented relevant to this first topic included results of studies concerning the geohydrology and geochemistry of commercially and Federally operated low-level radioactive-waste repository sites.

2. *Establishing guidelines for the geohydrologic siting and design of low-level radioactive-waste repositories in different geohydrologic and climatic environments.* This topic is inexorably tied to the lessons learned from study of low-level radioactive-waste repositories established in past years. Of the lessons learned from experiences at existing repositories, which need to be applied in the siting and design of the next generation of low-level radioactive-waste repositories?

3. *Characterizing and monitoring of potential low-level radioactive-waste repository sites.* What can be expected to be accomplished during this phase of study to provide geohydrologic data to assess the future effectiveness of a proposed repository? Can valid geohydrologic models of a potential repository site be developed from the data collected during the site-characterization study?

Manuscript approved for publication, August 12, 1988.

Each topic was assigned to a team of two participants at the workshop; the team prepared a written response to the questions posed by each topic and presented the paper to the workshop on the final day. Each team was assisted in its task by participants and speakers at the workshop who presented papers relevant to the assigned topics. The summaries of each of the three topics and the papers presented at the workshop are presented in this volume.

TOPIC SUMMARIES

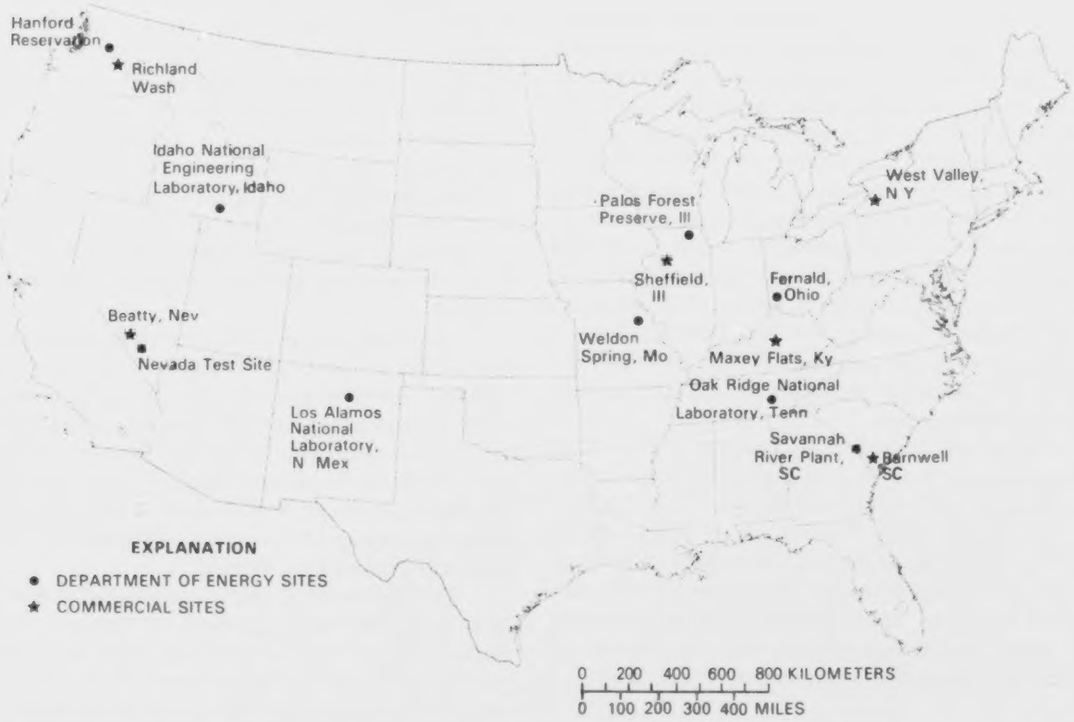
Topic I—Induced Changes in Hydrology at Low-Level Radioactive-Waste Repository Sites

By David E. Prudic *and* Kevin F. Dennehy

Engineering practices, including the excavation of trenches, placement of waste, nature of waste forms, backfilling procedures and materials, and trench-cover construction and materials at low-level radioactive-waste repository sites greatly affect the geohydrology of the sites. Engineering practices are dominant factors in eventual stability and isolation of the waste. The papers presented relating to Topic I were discussions of the hydrogeologic setting at existing low-level radioactive-waste repository sites and changes in the hydrology induced by site operations. Papers summarizing detailed studies presented at this workshop include those at sites near Sheffield, Ill.; Oak Ridge National Laboratory, Tenn.; West Valley, N.Y.; Maxey Flats, Ky.; Barnwell, S.C.; and Beatty, Nev.

Burial operations were similar at all sites. The land was cleared and regraded, and long shallow trenches were excavated for the disposal of low-level radioactive wastes. The process of regrading the land sometimes resulted in the filling of small natural drainages or in the oversteepening of slopes along incised streams with excess soil. Wastes packaged in a variety of containers were dumped or stacked, generally to the top of the trenches. The trenches then were covered with a meter or so of excavated material, the material was compacted, and the area around the trenches was regraded to promote runoff. Burial operations and trench construction evolved in an attempt to accommodate and rectify unforeseen problems with burial of the wastes in various geologic and hydrologic environments.

At some of the sites, the water table was at sufficient depth beneath the bottom of the trenches that seasonal variations in the water table did not cause water to come in contact with the buried waste. At some of the other sites, the water table fluctuated within the shallow depths at which the wastes were buried.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Fernald, Ohio
Beatty, Nev
Nevada Test Site
Weldon Spring, Mo
Maxey Flats, Ky
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0 100 200 300 400 MILES

Figure 1. Location of commercially operated and major Federally operated low-level radioactive-waste repository sites in the United States.

In humid areas, the practice of burying wastes in long, shallow trenches resulted in greater recharge through the trench covers into the trenches than what would occur naturally. At three sites—Oak Ridge, Tenn.; West Valley, N.Y.; and Maxey Flats, Ky.—recharge into the trenches exceeded percolation out of the trench floors and walls, and this resulted in a gradual filling of the trenches with water. Water continued to accumulate in the trenches at these sites until it overflowed at the land surface or was pumped from the trenches. This process commonly has been called the bathtub effect. The bathtub effect has not been a problem at the sites near Sheffield, Ill., and near Barnwell, S.C. There, water percolating through the trenches is not greatly retarded by the undisturbed deposits around the trenches, but instead moves out of the trenches through permeable deposits. Allowing the percolating water to pass quickly through a trench may be more desirable than having the water trapped in the trench for extended periods. The volume of water percolating through the wastes at the present sites has been decreased by improved trench design—mainly by increasing the trench-cover thickness, by greater compaction of the new trench covers, and through improved techniques of contouring the trench covers to control runoff.

Regrading of land surface at the sites in humid areas to promote runoff had the unintended result of accelerating trench-cover erosion. In addition, recharge to the trenches was increased by attempts to stabilize the soil with plants because this resulted in incomplete draining of runoff away from the trench area; in some instances, the revegetation allowed water to pond in depressions between trench covers. By combining the lessons learned at these sites with an improved understanding of the relation between recharge, evapotranspiration, runoff, and erosion, it is possible to design trench covers that effectively decrease infiltration into the trenches. Improved waste containers that isolate waste from percolating water, retain their shape, are stackable, and have shapes that minimize voids between containers could decrease collapse features in the trench covers, which tend to funnel precipitation directly into the trenches.

Little is known about the movement of water through trenches at the site near Beatty, Nev., which is in an arid area. Work to date has been on developing instrumentation and methods of estimating soil-moisture tensions under natural conditions. Plans are under way to study the effect trenches have on water movement in and adjacent to experimental trenches. This site seems to have the most favorable conditions for shallow-land burial of low-level radioactive wastes; minimal precipitation precludes much contact of the waste with water, the water table is many tens of meters below the wastes, and ground-water flow paths to points of discharge are many kilometers long. One unknown factor about this site is knowing what the effects of major floods would be. Such floods are infrequent and are difficult to monitor because of the long periods between floods and because of the uncertainty as to when a major flood will occur. Even though sites in arid areas seem to be the most favorable for burial of wastes, it is unrealistic to believe that all low-level radioactive wastes will be accepted for burial at these sites.

Initially, waste-disposal practices were understandably directed towards safe and efficient site operation. Little attention was given to the effects of these practices on the hydrology of a site. Now, increasingly sophisticated trench designs (improved covers, capillary barriers, drains, and so forth) are resulting from greater knowledge of changes in hydrology caused by waste-disposal practices, which has been acquired during the past three decades. The new designs are intended to minimize contact of water with the wastes, but long-term performance of these designs is largely untested. Thus, monitoring is still needed at all sites to assure minimal release of radionuclides to the environment.

Studies of radionuclide migration as gases generated from decomposition and volatilization of waste materials were done at the sites near Sheffield, Ill., and near West Valley, N.Y. Results of the studies indicate that substantial quantities of tritium and carbon-14 may be migrating away from the trenches either through the trench covers or through unsaturated deposits adjacent to the trenches. Such migration may be occurring at other sites, including sites in the arid West. The degree of gas formation depends on the quantity of water and oxygen available for the decomposition and volatilization of the waste.

Many test wells and piezometers were necessary to characterize the hydrogeology at most of the repository sites in humid areas—in particular, the complex geology near Sheffield, Ill., and at Maxey Flats, Ky. The complex glacial deposits at the site near Sheffield required more than 100 test wells to adequately define the extent of a pebbly sand that conducts water away from the trenches to a nearby lake. Similarly, many test wells were necessary to define a thin, fractured sandstone unit at the site at Maxey Flats, Ky., which conducts trench water to a nearby slope. Concerns about the abundance of test wells and some questionable well-construction practices in the past regarding the creation of conduits for radionuclide migration were discussed for several sites. No evidence was presented linking the abundance of test wells to migration of radionuclides. Some evidence was presented relating radionuclide migration to inadequately designed test wells.

The selection of geologic media as a host for waste disposal is extremely important. Aspects of the geology at present sites indicate the several limiting factors with regard to the geologic media. Burial of low-level radioactive wastes in shallow trenches excavated in rocks or deposits with minimal permeability in a humid area may not be feasible because of the difficulty and expense of making the trench covers as impermeable as the host media. Burial of wastes in fractured rocks or deposits results in uncertainties in monitoring and predicting the migration of radionuclides away from the wastes. Sites with complex geology require many test wells, thus extra expense, to adequately define ground-water flow paths and areas of recharge and discharge.

A major point brought out in the discussions of the present sites was that the hydrology and geology at a site needs to be sufficiently characterized in order to properly site a repository. Once a site has been characterized, appropriate waste-disposal procedures can be adopted that would be particularly suited to the specific environment. A standardized burial procedure may not be appropriate because of the unique characteristics of a site. Additionally, shallow-land burial has undergone numerous modifications at various sites, and, because of what we now know, engineered facilities may be unnecessary. With the implementation of totally new burial procedures comes potentially unforeseen problems that may result in a need to modify the new burial procedures to minimize exposures to the public.

Discussions after the presentation of papers at the meeting by working groups resulted in the following conclusions:

1. More emphasis needs to be given to understanding the climate at a site and the relation of climate to ground-water flow and waste-burial procedures.
2. Time required to adequately evaluate the geohydrology at potential waste-disposal sites should be dependent on the site's complexity and not on arbitrary time constraints.
3. Laboratory experiments and onsite testing of the concept of burial below the water table at selected locations are needed to determine the applicability of the technique in the United States.
4. Experienced geohydrologists were not comfortable with making predictions of site stability and risk assessment to the public for 300 to 500 years.
5. Trenches that are constructed to allow gases produced by biodegradation and volatilization of wastes to be released at a steady slow rate are preferred to those that are constructed to attempt to seal waste tightly so as to concentrate the gaseous radionuclides.
6. Although the one western site in an arid area seems to be well suited for burial of wastes, eastern sites in subhumid and humid areas, if properly selected and designed to account for the particular geologic and hydrologic conditions, may be adequate for the burial of low-level radioactive wastes.
7. Repository design and associated waste-burial procedures need to be compatible with the geologic and hydrologic setting of a site.

Topic II—Siting and Design of Low-Level Radioactive-Waste Repositories in Varied Geohydrologic and Climatic Environments

By William D. Nichols *and* Daniel J. Goode

Topic I of the workshop emphasized that the effectiveness of many repository sites is as much a function of the repository design and construction as it is a function of the natural geohydrology of the site. The exception to this conclusion is the case where the repository site is located in an arid area. The repository site in an arid area is considered a special case. Topic II is concerned with the effects of the geohydrologic setting in containment of low-level radioactive waste, geohydrologic-siting requirements for repository sites, and engineering designs for enhanced waste containment.

Waste generated during radioactive-element refining operations in the early 1900's commonly was disposed of at the processing site with no apparent regard for the health and environmental risks posed by the waste. Long-forgotten waste from pre-1920 radium-refining operations in the Denver, Colo., area were discovered in 1979. The wastes had been carelessly dumped at the refining site, probably because the radioactive substances were considered to be efficacious in treating human-health problems and there was no concern about the dumping of the wastes.

The earliest repositories for low-level radioactive waste were established by the Federal government for waste from national defense and research facilities. Until 1962, burial of low-level radioactive waste from non–Federal facilities commonly was on Federally operated sites. The method of burial was predominantly at shallow depths in trenches, as at the Savannah River Plant, Oak Ridge National Laboratory, Argonne National Laboratory, and Nevada Test Site. Apparently little regard was given during early burial operations to methods of packaging the waste, the geologic and hydrologic characteristics of the burial site, or the backfill and cover materials of the waste trenches.

Recognition of the problems that developed at low-level radioactive-waste sites, both commercially and Federally operated, prompted the development of more rigorous repository-siting criteria. Guidelines to overcome many of the problems associated with existing sites have been proposed by various investigators and interagency panels. Although a number of geohydrologic conditions have been declared favorable for low-level radioactive-waste burial, these guidelines have not been proven to be complete or adequate because no new sites have been developed since 1971. The next generation of low-level radioactive-waste repositories, those yet to be constructed, will ultimately prove if geohydrologists have provided adequate guidelines for site selection. Geohydrologists need to consider carefully the geohydrologic criteria necessary for a repository.

Only considering geohydrology, the ideal geohydrologic setting for a low-level radioactive-waste repository would be in an environment that has:

1. Minimal precipitation.
2. A granular porous medium.
3. A deep water table (deep for these purposes is 100 m or more).
4. No exposure to flooding or rapid erosion.

In addition to these criteria, there are other criteria that might be used to provide even more security against radionuclide migration, such as selecting areas with long ground-water flow paths, avoiding areas underlain by carbonate rocks, avoiding areas where there are active faults, selecting closed hydrologic basins, and other criteria listed elsewhere.

The characteristics of the site that provide the most confidence that the site will contain the waste are the lack of precipitation and the thick unsaturated zone beneath the buried waste. These characteristics are present throughout large areas of the semiarid and arid western and southwestern United States.

However, for a variety of social, economic, political, and other reasons, it may be necessary to establish low-level radioactive-waste repositories in subhumid and humid areas of the Nation. As indicated by the number of papers in this volume describing studies at sites in subhumid and humid areas, such locations have caused many problems because of transport of radionuclides, usually in the ground water, but sometimes in overland flow from flooded trenches. Site-selection criteria to include subhumid and humid areas become more extensive, and potential sites become more difficult to characterize and evaluate. Also questionable are the problems of locating sites for burial above the water table, of locating suitable host media, and of designing adequate means for burial below the water table.

First, consider the burial of waste above the water table. The list of siting guidelines is long; only those for which there is some consensus are listed here. They are as follows:

1. A water table deep enough so that buried waste is not saturated.
2. A definable flow system (there will be radionuclide transport, so where will the radionuclides be transported to).
3. Long ground-water flow paths to allow radionuclides to decay.
4. An unsaturated zone with hydraulic conductivity increasing downward.
5. Other guidelines, most of which are concerned with the movement of ground water and, by implication, the movement of radionuclides.

Additionally, discussions of siting low-level radioactive-waste repositories in subhumid and humid areas has elicited much discussion on the need for engineered containment structures. An opinion has been expressed by some geohydrologists that engineering design can improve an otherwise less than satisfactory site, but the U.S. Nuclear Regulatory Commission's (1982) stated position is that all sites must meet siting requirements, regardless of facility design. There has been much discussion of trench-cover design (see papers by Randall, Prudic, and Lyverse, this volume), water management over and near the trench cover (see paper by Hakonson and others, this volume), and capillary barriers (see paper by Reed, this volume). But for these to be effective, the problems of trench collapse need to be overcome; trench collapse occurs even at sites in arid areas. A variety of engineered structures that were discussed are intended to overcome the problems associated with waste and trench-cover collapse and with water infiltration; however, none of the structures, devised so far, not even the French earth-mounded concrete bunker, have yet demonstrated an ability to retain their effectiveness for the extended periods required. Nevertheless, there may be locations in subhumid and humid areas that can adequately isolate and contain low-level radioactive waste buried above the water table.

Waste burial below the water table is the second option for siting in subhumid and humid areas. The U.S. Nuclear Regulatory Commission's (1982) regulations for this option require that radionuclide transport by diffusion be the dominant transport mechanism. There are technological as well as economic problems associated with this option, but it is probable that there may be appropriate sites and that technology may be developed for suitable burial in the saturated zone.

Such sites will be difficult to locate, study, and characterize properly before waste burial takes place. Fundamental criteria that needs to be met are slow recharge rates, slow ground-water velocity, and consequently, minimal hydraulic conductivity in order to ensure that diffusion is the dominant process. Fracture flow needs to be avoided.

Questions immediately are asked regarding how conditions can be maintained so that diffusion continues to be the dominant transport mechanism. Construction and burial operations that enhance recharge resulting in trench saturation and overflow at the land surface need to be avoided. Waste-emplacement activities that change the conditions of diffusion-dominated transport also need to be avoided.

In conclusion, it is probable that not every State in the United States will have a suitable site for a low-level radioactive-waste repository—at least a site that is geohydrologically suitable. These States, if required to establish a site, will have to resort to expensive engineering solutions based on assumptions that have not yet been proved. Such solutions may not be necessary, however, if as part of the siting process, geohydrologists explicitly address the undesirability of copious precipitation and acknowledge the effect of climate in radionuclide migration.

There is a fundamental difference between the process of selecting a site in a semiarid or arid area and the process used in a subhumid or humid area. In the former, it is assumed that there will be little or no transport of radionuclides because of the lack of available water, and that the thick, unsaturated zone will provide adequate protection from exposure for long periods. In the latter, it seems to be assumed that transport of radionuclides is inevitable. Therefore, ground-water flow systems need to be well defined and understood, and compatible engineering solutions need to be developed to decrease, retard, eliminate, or mitigate the effects of the inevitable transport.

The establishment of favorable site requirements for a low-level radioactive-waste repository does not assure satisfactory containment of waste. The engineering design and construction of the repository need to be compatible with the geohydrologic setting. The geohydrology alone cannot assure an adequate repository. While the geohydrologists were busy formulating better guidelines for siting repositories, the engineers were busy designing enhanced isolation barriers and systems in an effort to complement the natural setting in isolating the waste. An overview of many of the engineered repository designs that are currently (1987) being considered is presented in the paper by Schwarz in this volume; an evaluation of several of these engineered repositories is given by Hinschberger in this volume. Hydrologists need to be cognizant of the interaction of the engineered repository and the hydrology, the long-term effectiveness of the repository, and other factors that will affect the effectiveness of a repository.

Reference

U.S. Nuclear Regulatory Commission, 1982, 10CFR61—Licensing requirements for land disposal of radioactive waste: Federal Register, v. 47, no. 248, p. 57446–57482.

Topic III.—Characterizing and Monitoring Low-Level Radioactive-Waste Repository Sites

By Kenneth L. Kipp *and* Richard W. Healy

Introduction

The purpose of site characterization and monitoring is to be able to understand repository effectiveness in order to predict with some level of confidence that the design criteria will be met. These criteria are designed to limit the exposure or dose of radioactivity to people. In order to apply the criteria to geohydrologic evaluation and solute-transport calculations, we need to translate the dose to a nuclide flux at some interface where liquids or gases that have passed through or emanated from a low-level radioactive-waste repository enter the environment.

Proper evaluation of the suitability of a proposed repository site and design requires a system analysis. In addition to geohydrologic investigations with associated conceptual modeling, the topics of uncertainty quantification, risk analysis, cost-benefit analysis, and optimal management strategy are pertinent to the evaluation. This session was concerned only with studying the geohydrology and geochemistry of surface and ground-water systems as they might affect the suitability of a site for a low-level radioactive-waste repository. In general, one can expect investigations that involve data collection and conceptual and quantitative modeling to identify some important limitations regarding site suitability indicated by the geohydrologic environment.

Summary of Presentations and Discussion

Seven papers were presented during this session describing many, but not all, aspects of geohydrologic characterization and monitoring of prospective low-level radioactive-waste repository sites. The topics discussed included surface-water flow, ground-water flow in the saturated and unsaturated zones, disposal in the saturated zone, geochemical modeling considerations, well-drilling and sampling techniques, borehole and surface geophysics, and a progress report of an actual site-selection and characterization process.

Edwin P. Weeks (this volume) presented his thoughts on geohydrologic characterization of low-level radioactive-waste repository sites. An idea that was to be expressed several times during the session was that geohydrologists cannot expect a site model to replicate all that is occurring at the site. Instead, simplified models can help test hypotheses and develop conceptual models of the major flow and transport mechanisms that are or could be present. These simplified models also might aid in identifying potential problems with repository effectiveness. In the unsaturated zone, it is important to identify the water-movement mechanism, be it nearly piston flow or macropore flow along preferential pathways. Tracer tests to evaluate this generally are not feasible within the 1 or 2 years usually allowed for site characterization, but preexisting natural tracers might be helpful. Water-balance calculations are not suited for arid-area studies. The effect and importance of using the detailed geology in formulating model concepts and parameter distributions generally has been neglected during quantitative modeling. Gas-phase transport may be a significant mechanism, but only a preliminary evaluation will be possible during a 1- or 2-year study. The question was asked as to whether one should start with the most complex and comprehensive model of a site that could be formulated and then simplify as allowed by the data obtained. Some believed that this approach would be too costly, and one needs to develop a site model from the simple to the more complex as the collected data warranted.

An alternative burial method for subhumid and humid areas, burial below the water table, was described by David E. Prudic (this volume). The prime site-characterization requirement for this approach is to demonstrate that the advective transport rate is negligible. This leaves molecular diffusion as the primary transport mechanism. A tracer test to quantify the diffusive transport rates would be desirable, but this would take longer than 1 year. The potential for methane gas generated from the waste becoming a radionuclide transport phase was suggested but not resolved. Also, the potential for organic compounds to change the permeability of the medium needs to be evaluated at a candidate site. Finally, the risk of excessive modification of the minimal permeability and storage of the porous medium by drilling and instrumentation was considered to be a valid concern for this type of burial.

Perspectives in geochemical modeling with emphasis on reaction identification were presented by Donald C. Thorstenson (this volume). This approach, which involves mass balances and thermodynamics, can enable one to identify possible major reactions. Minor reactions are much more difficult to define. For one example, the results were dependent on the set of chemical species and phases selected for modeling, and it was impossible to determine the definitive geochemical model for the site. Models based on aqueous chemistry are nonunique. Information on the solid phases is necessary, but such information is not sufficient to achieve a unique characterization of the geochemical system. However, the geochemical modeling can be related to the geohydrologic modeling and help to validate some hypotheses. Geochemical modeling can identify the type of system chemistry at a given site, which can result in characterization of important terms for radionuclide-transport simulation. The mass balance method is more useful than the reaction-path method. For the mass-balance method, sensitivity analyses performed with geochemical reaction modeling can be useful in understanding the chemical reaction environment.

Warren E. Teasdale (this volume) described drilling and sampling methods applicable to site characterization. The importance of early and complete planning to ensure the best results for the time and money spent on the drilling program cannot be overemphasized. The drilling and sampling methods used need to be suited to the geologic materials of the site and to the type of data to be obtained from the samples. Sometimes, trying to make one borehole serve for a multiplicity of purposes results in its being suboptimal for each of those purposes; separate boreholes would have been more cost effective.

The topic of geophysics was addressed by two speakers. Frederick L. Paillet (this volume) presented three new developments in borehole geophysics. He emphasized the importance of site-specific calibration for two reasons: (1) The fact that geophysical methods measure properties that are not uniquely related to the geohydrologic properties, and (2) that the sample volume of a geophysical probe is much larger than the sample volume of material extracted and used for the direct measurement of a geohydrologic or transport property. Many samples need to be extracted to perform an accurate calibration; this is a necessary cost of geophysical methods. Most borehole-geophysical techniques were developed by the petroleum industry and may not be optimally suited for geohydrologic investigations. As many types of borehole logs need to be obtained as are applicable because the major cost is associated with obtaining the first borehole log and because of the nonunique associations between the set of geophysical properties measured and the geohydrologic properties desired.

Gary R. Olhoeft (this volume) described three of the newer, more sophisticated surface-geophysical techniques available. In general, the resolution of surface-geophysical measurements decreased with depth; however, these methods provide the quickest means of quantifying a site. Not all geophysical techniques will work at all sites, but one needs to use all that are possible for the reasons given above for borehole geophysical methods. Site-specific calibration is needed for quantitative information to be obtained from most surface-geophysical methods.

The concluding talk of the session was a discussion by Greg Hamer of the current (1987) site screening and characterization program used by State agencies in California for a low-level radioactive-waste repository. Many aspects of site characterization previously presented in this session have been applied in this ongoing study. An important idea discussed was that the repository-site operator, the geohydrologist, and the public, as represented by the regulator, each have different perspectives and priorities connected with site characterization. The repository-site operator wants to meet the site-qualification requirements in the shortest time with a minimum expenditure of money, whereas the geohydrologist wants to learn as much about the site as possible in order to maximize confidence in the performance predictions. The regulator wants the quantity and quality of the information of the geohydrologist, but at the time and cost limitation of the repository-site operator. Clearly, many compromises need to be made. It seemed that the requirement of 1 year of study for this site actually would require about 3 years of work.

The final discussion period was basically a review of the topics discussed during the presentations. However, it was recognized that quantitative modeling and stochastic modeling in particular had not been discussed in depth during the session. There was a collective lack of expertise in the areas of statistical methods and stochastic modeling. It was believed that quantitative modeling needs to be used as an aid to developing a conceptual model of a site. A usefulness of the conceptual model is in relating the data collected, testing hypotheses, and quantifying estimates of performance of a repository site. However, any predictions of performance need to have uncertainty estimates associated with them in order to properly assess their significance.

Conclusions

We concluded that adequate characterization of a proposed low-level radioactive-waste repository site can be achieved, but not within 1 to 2 years. Possibly 5 years may be needed to decrease uncertainties associated with quantification of hydrologic-transport mechanisms to desired ranges. The scope of the studies needed to support the type of site characterization described in 10CFR61 (U.S. Nuclear Regulatory Commission, 1982) is simply too large to accomplish within 1 to 2 years. It is possible to develop valid conceptual and quantitative models, but they will be simplified representations of major mechanisms and characteristics and not comprehensive or definitive analogs of the site. The possiblity of nonuniqueness of a quantitative model always will be present. One of the most useful exercises to be done with a model is a sensitivity analysis. Uncertainty estimates for predicted performance can be obtained from a sensitivity analysis.

Some elements of site characterization that are not currently (1987) achievable include: (1) Rigorous quantification of uncertainties of geohydrologic and geochemical models, (2) establishment of unique and comprehensive models, (3) identification and quantitative characterization of new or nonstandard transport mechanisms (particularly coupled ones), and (4) knowledge of source terms for radionuclides migrating from the containment structure. The first item is currently emerging from the theoretical development to initial applications. The fourth item can be addressed by good recordkeeping and experimental determination of leach rates from the various waste materials, although the cost of achieving this may be prohibitive.

Topics for further research include: (1) Further investigation of the suitability of low-level waste burial in the saturated zone of formations with minimal permeability, and (2) developing methods for applying stochastic methods to site characterization to quantify uncertainties associated with model predictions.

Reference

U.S. Nuclear Regulatory Commission, 1982, 10CFR61—Licensing requirements for land disposal of radioactive waste: Federal Register, v. 47, no. 248, p. 57446–57482.

PAPERS

Surface Hydrology at the Low-Level Radioactive-Waste Repository Site Near Sheffield, Illinois

By John R. Gray

Introduction

Processes relating to runoff, sediment transport, surface collapse, and erosion were evaluated at the low-level radioactive-waste repository site near Sheffield, Ill. (fig. 2) and at a nearby undisturbed basin. Runoff was measured to provide data for computation of sediment transport and to define one component of the hydrologic budget. Sediment transport was computed to estimate fluvial erosion from the site. Surface collapse and erosion were studied because they are the principal landform modifications presently (1987) affecting the site. Similar types of measurements were made at the nearby undisturbed basin to provide a reference to results obtained onsite.

Runoff and sediment transport were measured in four basins—three basins composing almost two-thirds of the 8.1-ha repository site and a 1.4-ha basin offsite in undisturbed terrain—from July 1982 through December 1985 (fig. 3). Runoff also was measured from four small plots averaging 10.6 m^2 in size. Two of the small plots were on trench covers; the other two were within the undisturbed basin.

Volumes and equivalent weights of collapsed material at the site were evaluated from records of surficial conditions made by the site contractor from October 1978 through September 1985. Site inspections were performed at least monthly and more often during and after periods of rainfall or snowmelt. Information recorded during the inspections usually included approximate dimensions and locations of collapse cavities relative to trench boundaries. Cavity dimensions were used to compute cavity volumes. An estimate of the volume of material used to fill cavities also was occasionally noted. Weights of collapsed material were computed from cavity volumes and a mean bulk density of 1.56 g/cm^3 determined for surficial material at the site.

Runoff

Precipitation measured from July 1982 through December 1985 averaged 889 mm annually; this was 365 mm less than the 36-year annual mean for the area based on records from nearby National Weather Service stations.

Runoff at the continuous record gages only occurred during and immediately after rainfall or snowmelt. Mean annual runoff from repository-site basins was compared to the 38 mm of mean annual runoff from the undisturbed basin. The ratio of runoff to precipitation averaged 0.13 and 0.23 during the growing (May through October) and dormant (November through April) seasons, respectively. Runoff had a direct relation to land use; smallest runoff was measured from the undisturbed basin, and largest runoff was measured from the two site basins comprised wholly of modified terrain. The relation of mean runoff to mean basin slope was indeterminant, most likely because of the markedly different land use.

The two principal differences between the repository site and adjacent undisturbed basin are: (1) Surficial material at the repository site has a comparatively greater bulk density resulting from inadvertent compaction by heavy machinery during and after burial, and (2) vegetation at the repository site tends to be shorter and less dense than that offsite. Onsite conditions should favor runoff over infiltration. Also, sparse vegetation offers comparatively little resistance to flow. This permits precipitation on trench areas to run off quickly, allowing comparatively little water to infiltrate.

Sediment Transport

Sediment yield measured onsite averaged 3.34×10^3 kg/ha annually from July 1982 through December 1985. This corresponds to about 0.25 mm gross erosion from the 8.1-ha site surface per year. It also is about one-third the sediment yield expected from a 8.1-ha, 8-percent-slope basin used for row-crop agriculture near Sheffield (Khanbilvardi and Rogowski, 1984, p. 866; Alan Madison, U.S. Soil Conservation Service, oral commun., 1985). Most sediment transported from the site was eroded from bare areas, rills, and gullies.

Sediment yields from basins on the repository site were related to mean basin slopes. However, the mean

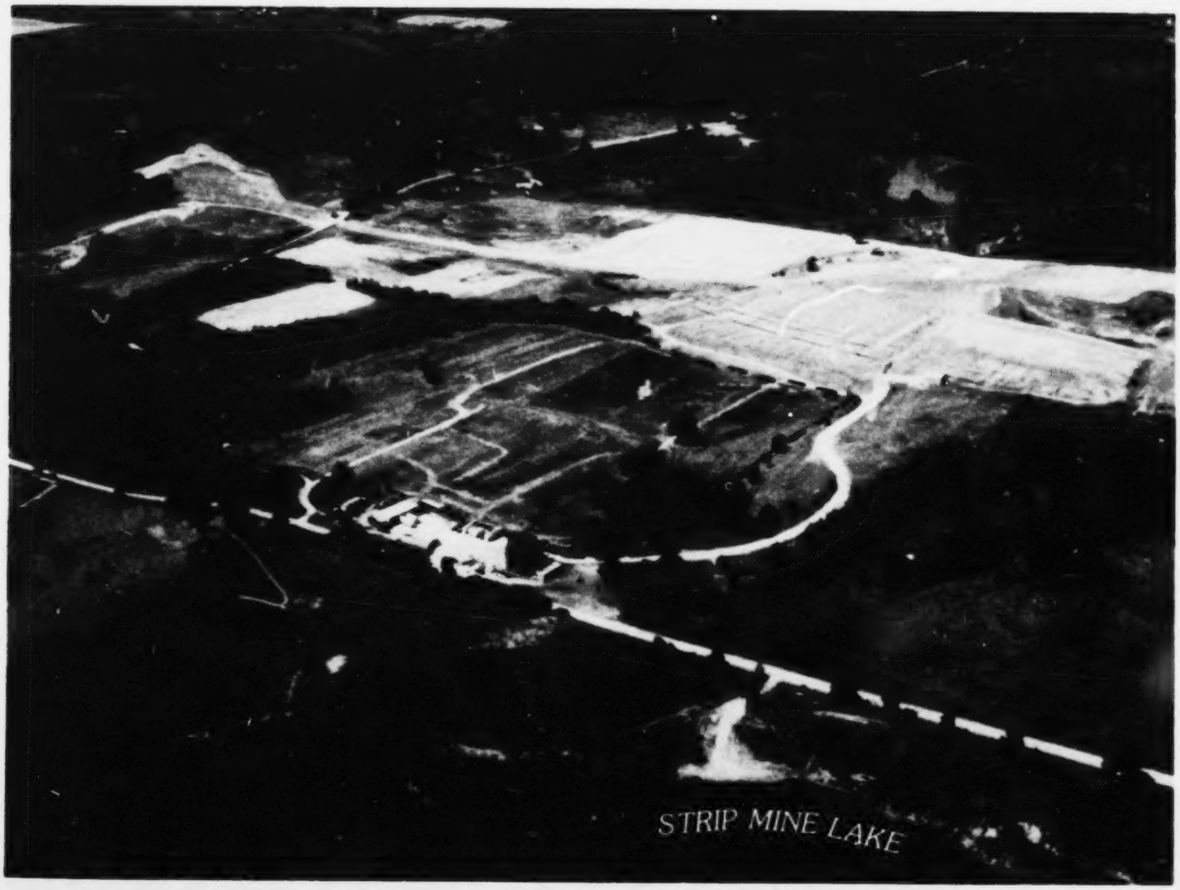

Figure 2. Low-level radioactive-waste repository site near Sheffield, Ill., 1985.

sediment yield from the undisturbed basin, which has the steepest mean slope of the gaged basins, was about two orders of magnitude less than mean sediment yields from basins on the site. The results indicate that land use has the greater effect on sediment yields and obscures the effect of mean basin slope and other landform character-

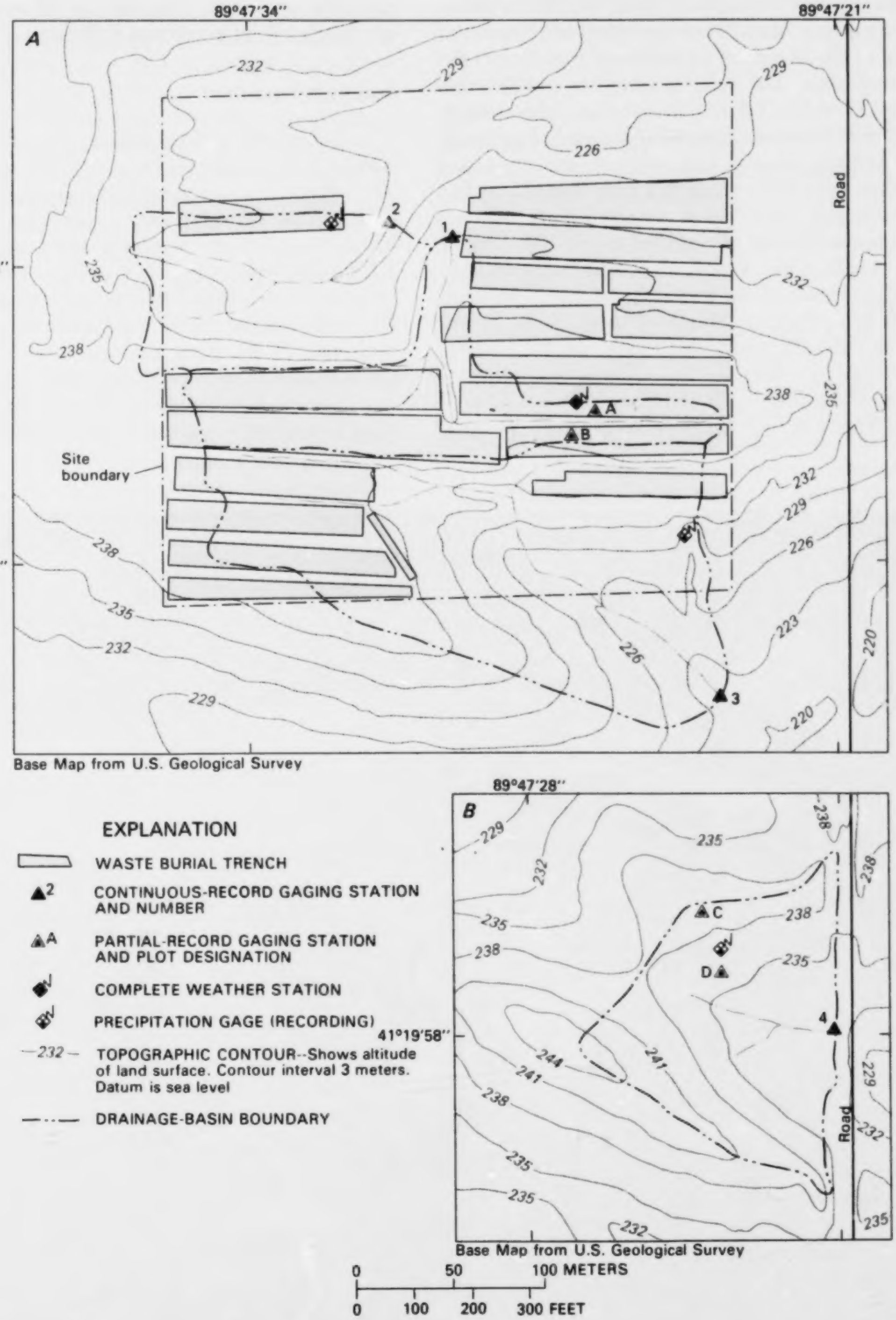
89°47'34"
89°47'21"
A
232
229
229
226
Road
2
1
41°20'22"
235
232
238
238
235
A
B
Site boundary
232
229
226
41°20'17"
238
235
232
226
223
220
229
3
220
Base Map from U.S. Geological Survey
EXPLANATION
WASTE BURIAL TRENCH
▲2 CONTINUOUS-RECORD GAGING STATION AND NUMBER
▲A PARTIAL-RECORD GAGING STATION AND PLOT DESIGNATION
COMPLETE WEATHER STATION
PRECIPITATION GAGE (RECORDING)
—232— TOPOGRAPHIC CONTOUR--Shows altitude of land surface. Contour interval 3 meters. Datum is sea level
—··— DRAINAGE-BASIN BOUNDARY
89°47'28"
B
229
232
235
238
238
235
C
238
238
D
235
41°19'58"
4
244
241
241
238
229
Road
232
235
235
232
235
Base Map from U.S. Geological Survey
0
50
100 METERS
0
100
200
300 FEET

Figure 3. Topography and surface-drainage divides: *A*, At the low-level radioactive-waste repository site; and *B*, In the undisturbed basin near Sheffield, Ill., 1982.

istics. In the absence of marked differences in land use, the effects of basin characteristics, such as mean basin slope and density of vegetation, become more pronounced.

Collapse

A total of 302 collapse cavities, corresponding to a cumulative volume of 496 m^3, was documented onsite from October 1978 through September 1985 (Kahle and Rowlands, 1981, p. 124–165; U.S. Ecology, Inc., written commun., 1983, 1984, 1985). Volume data for collapse cavities were distributed log-normally around a median of 3 mm^3. Although few cavities had depths or widths that exceeded 3 m, one was estimated to have a depth of 6 m, and two were estimated to have widths of about 5.5 m.

The location of collapse cavities relative to trench and site boundaries are shown in figure 4. Collapse cavities were distributed irregularly. Sixty-two percent of the collapse cavities occurred in swales between trenches or near trench boundaries; the remainder occurred in trench covers. Some trenches were more susceptible to collapse than others. More than two-thirds of the cumulative cavity volume was associated with trenches 1, 7, 10, 14A, and 24.

Most collapse cavities were recorded after rainfall or snowmelt when soil moisture was almost maximum. Two-thirds of the collapse cavities corresponding to 63 percent of the cumulative cavity volume occurred in February, March, and April. Three cavities documented in March and April 1979, after a record maximum winter precipitation, composed 30 percent of the total cavity volume.

The cumulative number and volume of collapse cavities for the 7-year period of record are shown on figure 5. A mean of 43 collapse cavities averaging 1.6 m^3 per cavity occurred annually. Since 1982, the mean annual number of collapse cavities has increased, but the mean size of each collapse cavity has decreased.

Trench covers and surrounding areas (trench area) compose about one-half of the 8.1-ha site. On the basis of

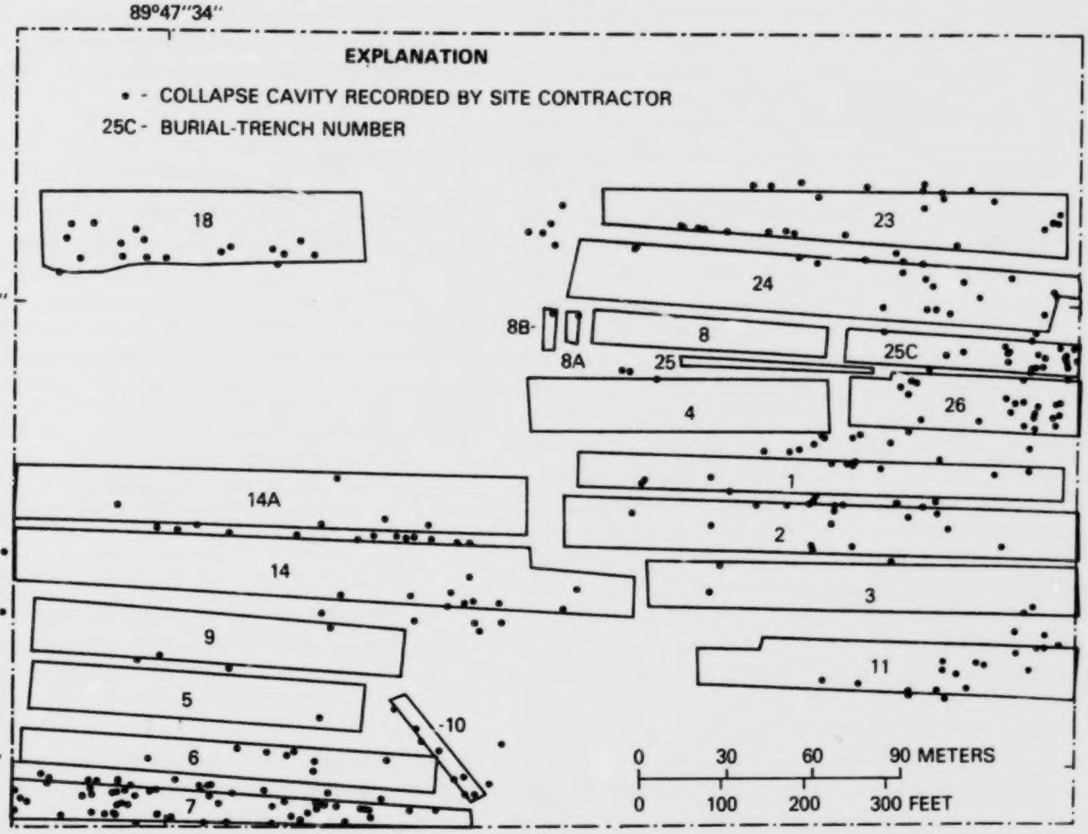

Figure 4. Location of collapse cavities relative to burial-trench and site boundaries at the low-level radioactive-waste repository site near Sheffield, Ill., October 1978 through September 1985. Most collapse cavities occurred in swales between trenches or near trench boundaries.

the weight of surficial material equivalent to collapse-cavity volumes, 7.7×10^5 kg of surficial material corresponding to an annual average of 2.7×10^4 kg/ha of trench area collapsed from October 1978 through September 1985. This corresponds to a mean 0.18-cm decrease in the altitude of the trench area.

Temporal Relations in Land-Surface Hydrology

Low-level radioactive-waste repository sites in humid areas can have short-, medium-, and long-term effects on the land-surface hydrologic system. During the short term, including the time of excavation and burial of the waste through the initial trench-cover stabilization, measured in months or years, disequilibrium predominates. Runoff and erosion generally are maximum. Collapse cavities result primarily from consolidation of fill material around wastes. Medium-term effects, the time measured in years or decades after burial, are characterized by more passive hydrologic responses. Although runoff and erosion may decrease substantially, they will remain greater than those for undisturbed conditions. Degradation of waste containers becomes an important factor in the formation of collapse cavities. Long-term effects on land-surface hydrology, the time of decades or longer after burial, are, in part, dependent on site management. If management practices continue, such as mowing and repairing erosion-or collapse-damaged areas, runoff and sediment transport probably will remain greater than those expected for natural conditions. Without continued management, land-surface hydrology responses will become similar to those for natural conditions. The formation of collapse cavities should decrease with or without management, owing to the near complete degradation of wastes and compaction of trench contents.

Data collected for runoff, sediment transport, and collapse-cavity formation at the site are characteristic of short- to medium-term hydrologic effects. Land-surface hydrologic responses of the undisturbed basin represent a long-term endpoint for those expected for the site if it is eventually left unmanaged. With continued management of the site, and barring any extraordinary modifications to the land surface or trench contents, the following is likely:

1. Runoff and sediment transport will gradually decrease until they are similar to or somewhat greater than those at the undisturbed basin. The decrease in runoff will result in soil-moisture increases from infiltration. During the growing season, this water likely will be evapotranspired. In the dormant season, additional recharge to the saturated zone likely will take place.
2. Mean collapse-cavity volume gradually will decrease because of more complete waste degradation and compaction. However, for years to come, collapse cavities will continue to be associated with the dormant season and conditions that cause general flooding in northern Illinois.

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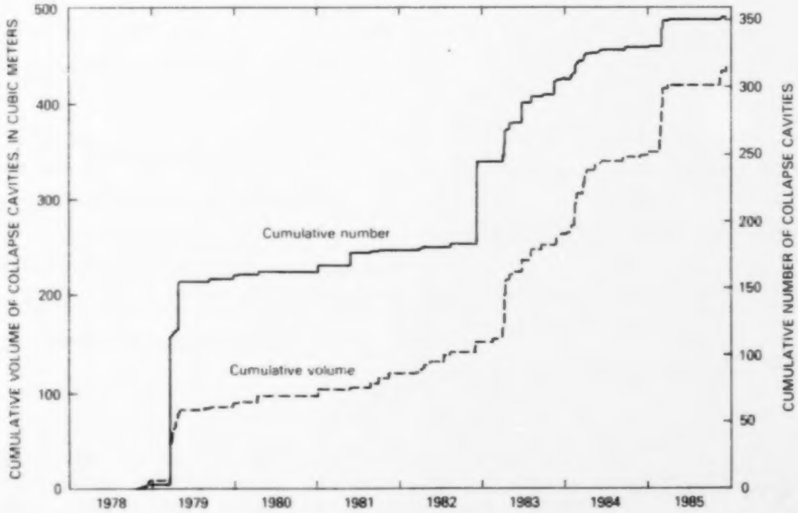

Figure 5. Cumulative number and volume of collapse cavities at the low-level radioactive-waste repository site near Sheffield, Ill., October 1978 through September 1985. Since 1982, the mean annual number of collapse cavities has increased, but the mean size of each collapse cavity has decreased.

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Results of Some Geohydrologic Studies at the Low-Level Radioactive-Waste Repository Site Near Sheffield, Illinois

By Richard W. Healy

The low-level radioactive-waste repository site is located on about 8 ha of rolling terrain 5 km southwest of Sheffield, Ill. The U.S. Geological Survey began investigating the site in 1976. Since then, studies have been completed on the following topics: hydrogeology, ground-water and solute movement within the unsaturated zone, water and tritium movement within the saturated zone, surface runoff and sediment transport, evapotranspiration, water movement through a trench cover, hydrogeochemistry of the unsaturated zone, and chemistry of gases within the unsaturated zone. The purpose of this presentation is to summarize the results of some of these studies. Specifically, results are presented on hydrogeology, water and tritium movement within the saturated zone, and water movement through the trench cover. In addition, results of all the studies are combined to present a conceptual model of the water balance at the site.

The shallow hydrogeologic system is composed of glacial deposits whose complex stratigraphy was defined from a study of continuous core samples from about 100 test wells and a 130-m-long tunnel that extended under four waste trenches (Foster and Erickson, 1980; Foster, Erickson, and Healy, 1984; Foster, Garklavs, and Mackey, 1984a). A thick sequence of Pennsylvanian shale and mudstone isolates the regional aquifers below from the hydrogeologic system in the overlying glacial deposits. These deposits consist of the Glasford Formation of Pleistocene age (Willman and Frye, 1970); Roxana Silt, Peoria Loess, and Cahokia Alluvium of Holocene age (Willman and Frye, 1970); and the deposits range from silty clay to coarse sand. A continuous, pebbly sand deposit forms the most permeable unit, underlying 67 percent of the site. The pebbly sand extends across the middle of the site continuing offsite to the northeast and southwest.

Flow in the shallow aquifer is within three ground-water basins (fig. 6); all ground water in these basins ultimately discharges into a strip-mine lake (Garklavs and Healy, 1986). Two principal ground-water flow paths were identified. The pebbly sand deposit conveys ground water and tritium eastward from the site to the strip-mine lake in the largest basin (basin 1), which drains about 70 percent of the site. Ground water in the other two basins (basins 2 and 3) is directed toward Lawson Creek before flowing toward the strip-mine lake. Results of digital modeling refined the conceptual models for two of the basins (basins 1 and 2) and provided estimates of ground-water velocities, directions of ground-water flow, and recharge rates for the basins modeled.

In ground-water basin 1, ground-water velocity through the pebbly sand was measured at about 750 m/yr in a buried channellike depression (Garklavs and Toler, 1985). Tritium was detected in ground water along the entire channellike depression, as well as in seeps along the bank of the strip-mine lake. It is estimated that about 100 mCi of tritium are discharged through these seeps annually. Except for water from one well in ground-water basin 2, there is no extensive offsite migration of tritium in the other two basins. The flow path from the site to the one well yielding water containing tritium at a concentration greater than background concentration is not defined. Tritium concentrations in ground water ranged from the detection limit (about 0.20 nCi/L per liter) to about 300 nCi/L.

Trench covers, originally designed to prevent the infiltration of moisture from precipitation, are only partially effective (Healy, 1983a). Data collected from instruments installed on and adjacent to a trench cover indicate that water movement into trenches occurs primarily along the periphery of the cover and secondarily through the center of the cover.

Waste trenches were constructed by an excavation and fill procedure. As waste was placed in a trench, it was covered with a silty material. After a trench was filled, it was covered with compacted clayey silt that was mounded lengthwise. The total thickness of the trench covers ranged from 1 m at the edge of the trench to 2 m at the center. Small swales between adjacent trench covers facilitate runoff of precipitation.

Tensiometer clusters were located at the crest of a trench cover (middle of trench), the swale between two covers, and on the slope of the cover halfway between the crest and swale. Depths of measurement ranged from 0.05 m to 2 m. Soil tensions were recorded continuously with pressure transducers and analog recorders. Soil-moisture content was measured weekly with a gamma-attenuation moisture probe.

Results indicate that most of the water that entered the trench did so along the trench periphery. There are two reasons for this: (1) The trench cover was thicker and had a lesser hydraulic conductivity at the center than at

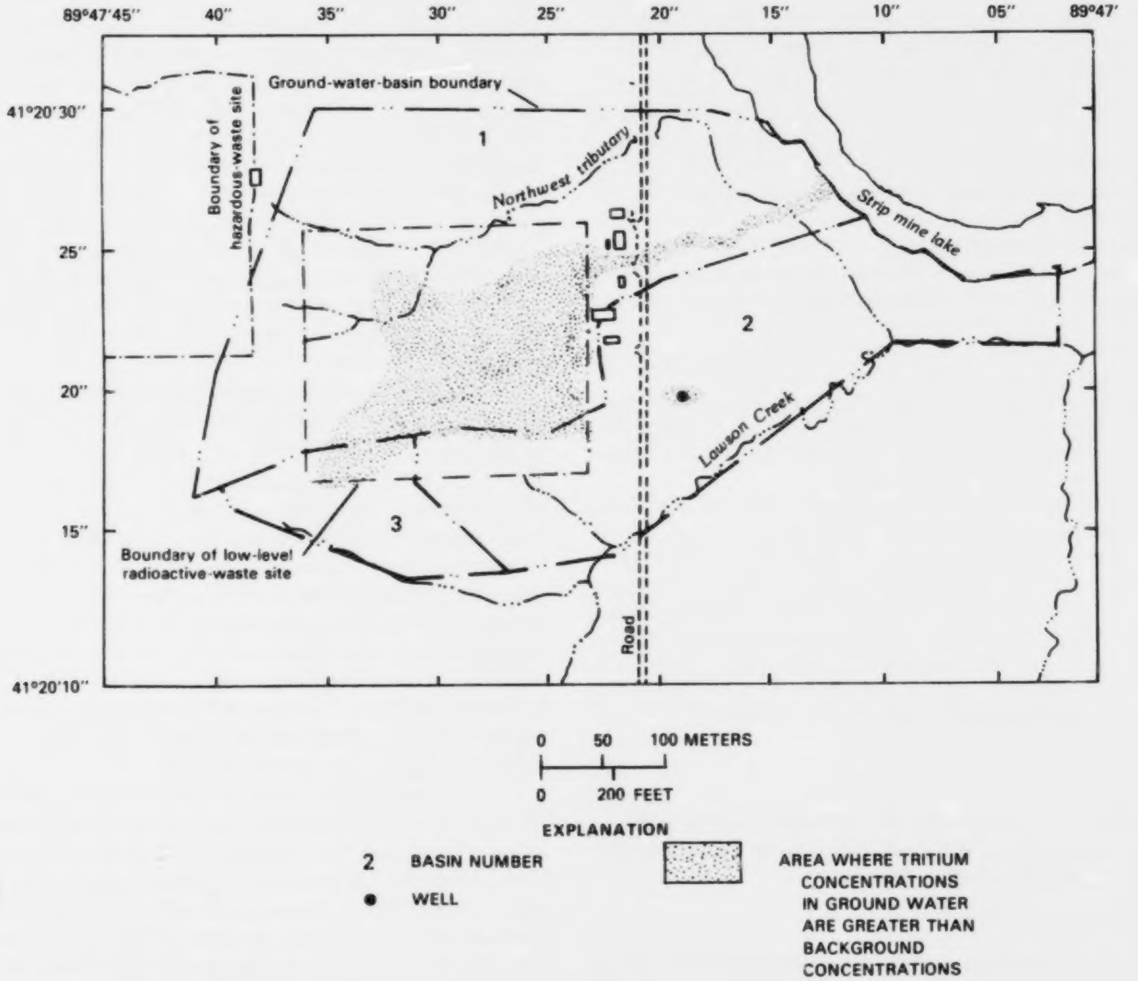
89°47'45"
40"
35"
30"
25"
20"
15"
10"
05"
89°47'
41°20'30"
25"
20"
15"
41°20'10"
Ground-water-basin boundary
Boundary of hazardous-waste site
1
2
3
Northwest tributary
Strip mine lake
Lawson Creek
Boundary of low-level radioactive-waste site
Road
0
50
100 METERS
0
200 FEET
EXPLANATION
2 BASIN NUMBER
● WELL
AREA WHERE TRITIUM CONCENTRATIONS IN GROUND WATER ARE GREATER THAN BACKGROUND CONCENTRATIONS

Figure 6. Location of low-level radioactive-waste repository site near Sheffield, Ill., ground-water basins and areas where tritium concentrations in ground water are greater than background concentrations. A pebbly sand aquifer conveys ground water and tritium eastward from the site to the strip-mine lake from basin 1, which drains about 70 percent of the site. Ground water in basins 2 and 3 is directed toward Lawson Creek before flowing toward the strip-mine lake.

the edge of the trench, and (2) water from precipitation tended to pond in swales between adjacent trenches. In the center of the trench, the compacted layer did impede the movement of water into the trench. Antecedent soil-moisture content was the most important variable affecting the rate and volume of water moving into the trench. Most of that movement occurred in early spring.

Detailed information is available for the water budget at the site from July 1982 to June 1984. During that time, annual precipitation averaged 938 mm; this average is similar to the long-term average for the area, 889 mm. Evapotranspiration was estimated to average 657 mm/yr (Healy and others, 1987). Surface runoff from the site averaged 160 mm/yr (Gray and Peters, 1985). It is assumed that most, if not all of the remaining 121 mm of precipitation recharged the saturated zone because there was no apparent change in soil-moisture content within the unsaturated zone. From May through September, evapotranspiration and runoff were greater than precipitation; hence, there was a net loss of water from the geohydrologic system. During the remaining months, precipitation exceeded evapotranspiration and runoff, producing a net increase in water in the system. Moisture content of the surficial deposits was greatest in March and April. This is the time when water movement through the waste trenches most likely occurred.

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Burial Grounds for Low-Level Radioactive Waste at Oak Ridge National Laboratory, Tennessee

By David A. Webster

Introduction

The practice of burying low-level radioactive waste at the Oak Ridge National Laboratory (ORNL), Tennessee, began during World War II and has continued for more than 40 years. To date (1987), six burial grounds have been used (table 1), and an area for a seventh burial ground has been studied. Evidence from numerous onsite studies during the past 10 to 15 years indicates that some of the biologically hazardous radionuclides emplaced in the ORNL burial grounds have been transported from them and discharged to local drainages. Transport has resulted from both environmental factors and operational practices.

Geohydrologic Setting

The ORNL is located in the corrugatedlike terrain of the Ridge and Valley Province. The first three burial grounds that were developed are located in Bethel Valley, which is underlain by the Chickamauga Limestone of Ordovician age (fig. 7). The formation consists predominantly of limestone, but it also includes some thin-shale intervals. A geologic study (Stockdale, 1951) during the late 1940's indicated that the limestone contains solution cavities of small cross-sectional area. Stockdale (1951) warned that it was inevitable for ground water below the burial grounds to become contaminated. Because transport pathways in cavernous media were considered unpredictable, a recommendation was made that the burial grounds be relocated in the "Conasauga shale belt" of Melton Valley, the adjacent valley to the southeast.

The lithology and structure of Melton Valley, which is complex, was little understood at that time. Melton Valley is underlain by six formations of the Conasauga Group of Cambrian age, five of which underlie the waste disposal areas. From oldest to youngest, their lithology is interbedded noncalcareous siltstone and mudstone that locally is termed "shale"; interbedded calcareous mudstone and siltstone; noncalcareous mud-

Table 1. Summary of burial-ground data, Oak Ridge National Laboratory, Tenn.

Bethel Valley	Years of operation	Area (hectares)	Melton Valley	Years of operation	Area (hectares)
Burial ground 1	1944–46	0.4	Burial ground 4	1951–59	9.3
Burial ground 2	1944–46	1.5	Burial ground 5 exclusive of transuranic storage area	1958–73	23
Burial ground 3	1946–51	2.5	Burial ground 6	1973 to present	28

Table 2. Average hydraulic-conductivity values for the regolith of burial grounds 4, 5, and 6, and the bedrock of burial ground 5, Oak Ridge National Laboratory, Tenn.

[– –, no data]

Geologic unit	Average hydraulic conductivity, in meters per day		
	Burial ground 4	Burial ground 5	Burial ground 6
Regolith	1.8×10^{-2}	1.1×10^{-1}	1.4×10^{-1}
Bedrock—depth interval, in meters			
15–30	– –	1.1×10^{-2}	– –
30–46	– –	9.7×10^{-3}	– –
46–61	– –	3.0×10^{-3}	– –

stone and siltstone; interclastic limestone interbedded with mudstone; and mudstone interbedded with calcareous siltstone (Haase and Vaughn, 1981). Large blocks have been moved along tear faults and thrust faults; these blocks have a regional dip to the southeast. Within the blocks, beds have been deformed by innumerable folds, faults, fractures, and slippages along bedding planes.

Regoliths of the Chickamauga Limestone and Conasauga Group are the host media for all of the burial waste. The regolith of the Chickamauga Limestone primarily consists of silt and kaolinitic, illitic, and possibly montmorillonitic clays (McMaster and Waller, 1965). Near burial ground 3, the regolith thickness increases westerly from zero at bedrock outcrops east of the site to about 7 m a short distance west of the site boundary. Hydraulic-conductivity measurements have not been made, but hydraulic conductivity is inferred to be minimal. Only cursory geohydrologic information is available for burial grounds 1 and 2, of which little study has been made and for which no records were kept.

The regolith of the Conasauga is far more variable than that of the Chickamauga. It consists of silt, clay, pebbles, and rock fragments, with the deformed structure of the bedding still plainly visible. The principal clay minerals are illite and vermiculite (McMaster and Waller, 1965). Thicknesses range from about 1 m near the drainages to as much as 12 m near the broad summits of burial grounds 5 and 6, but the thicknesses are very irregular, particularly in the interbedded clastic and carbonate strata. The average hydraulic conductivity is minimal, although the range in values spans two to three orders of magnitude. Some averaged hydraulic-conductivity values for the burial grounds in Melton Valley, based on slug tests of wells, are given in table 2. The small value for burial ground 4 relative to burial grounds 5 and 6 is due to developing that site in the regolith of siltstone and mudstone as opposed to the regolith of the interbedded calcareous siltstone and limestone. Average distribution coefficients of the local clay for a few of the biologically hazardous radionuclides are given in table 3. The extremely large value of illite for Cs renders this radionuclide almost immobile in a dissolved state in the regolith of the Conasauga. When detected in water from wells or in streams, this radionuclide usually is attached to particulate matter. Co and Sr, having smaller distribution coefficients, are transported more readily in solution through the weathered materials.

The ORNL area is drained by Whiteoak Creek, a stream about 6.5 river km long that receives contaminants from many sources. After entering Melton Valley, it incorporates the flow of Melton Branch, its principal tributary, and then discharges into the Clinch River, which flows along the eastern and southern boundaries of the ORNL. Ground water below all of the burial grounds discharges to the Whiteoak Creek drainage. Ground water below burial ground 3, which straddles a ground-water divide, also discharges into the Raccoon Creek drainage. In Melton Valley, most of the recharge to the ground-water reservoir—probably more than 90 percent—flows through the regolith only, as is evidenced by the difference in average hydraulic-conductivity values of the regolith and bedrock (table 2). In contrast, most of the recharge to burial ground 3 flows from the regolith to the bedrock before discharging into the drainage network.

Precipitation varies substantially, both monthly and annually. Between 1954 and 1983, average annual precipitation was 1,326 mm, greater than that at any of the other low-level radioactive-waste repository sites in the United States. The relation of climate, particularly precipitation, to repository-site effectiveness warrants em-

Table 3. Average distribution coefficients of local clay minerals for cesium-137, cobalt-60, and strontium-85, Oak Ridge National Laboratory, Tenn.

[Values (Morton, 1961) are for distilled water at pH 6 after 7 days (vermiculite, after 8 days). Tap water may greatly decrease coefficients for strontium-85 because of competition by calcium ions (Carrigan and others, 1967)]

Radionuclide	Average distribution coefficients for indicated clay minerals			
	Illite	Kaolinite	Montmorillonite	Vermiculite
Cesium-137 (^{137}Cs)	180,000	2,200	1,000	12,000
Cobalt-60 (^{60}Co)	6,400	3,100	1,700	4,700
Strontium-85 (^{85}Sr)	370	4,000	2,100	1,800

phasis. As noted by Richardson (1963), precipitation: (1) Maintains the water-table position, which is at shallow depth in the regolith and bedrock underlying the ORNL; (2) affects the physical and chemical characteristics of the regolith, particularly pH and types and proportions of clay minerals, and the characteristics in turn affect sorptive and ion-exchange capacity of the media; (3) markedly affects drainage density, which determines distances that contaminants travel before being discharged into a stream, length of time in transport, and effective volume of media available for sorption and ion exchange (because the distance between drainages in Melton Valley seldom is greater than 600 m, burial grounds 4, 5, and 6 have streams within them as well as around them); (4) provides for the dilution of contaminants released to streams; and (5) affects the composition of the biological community of the area, which is a problem when contaminants are assimilated by organisms in the food chain.

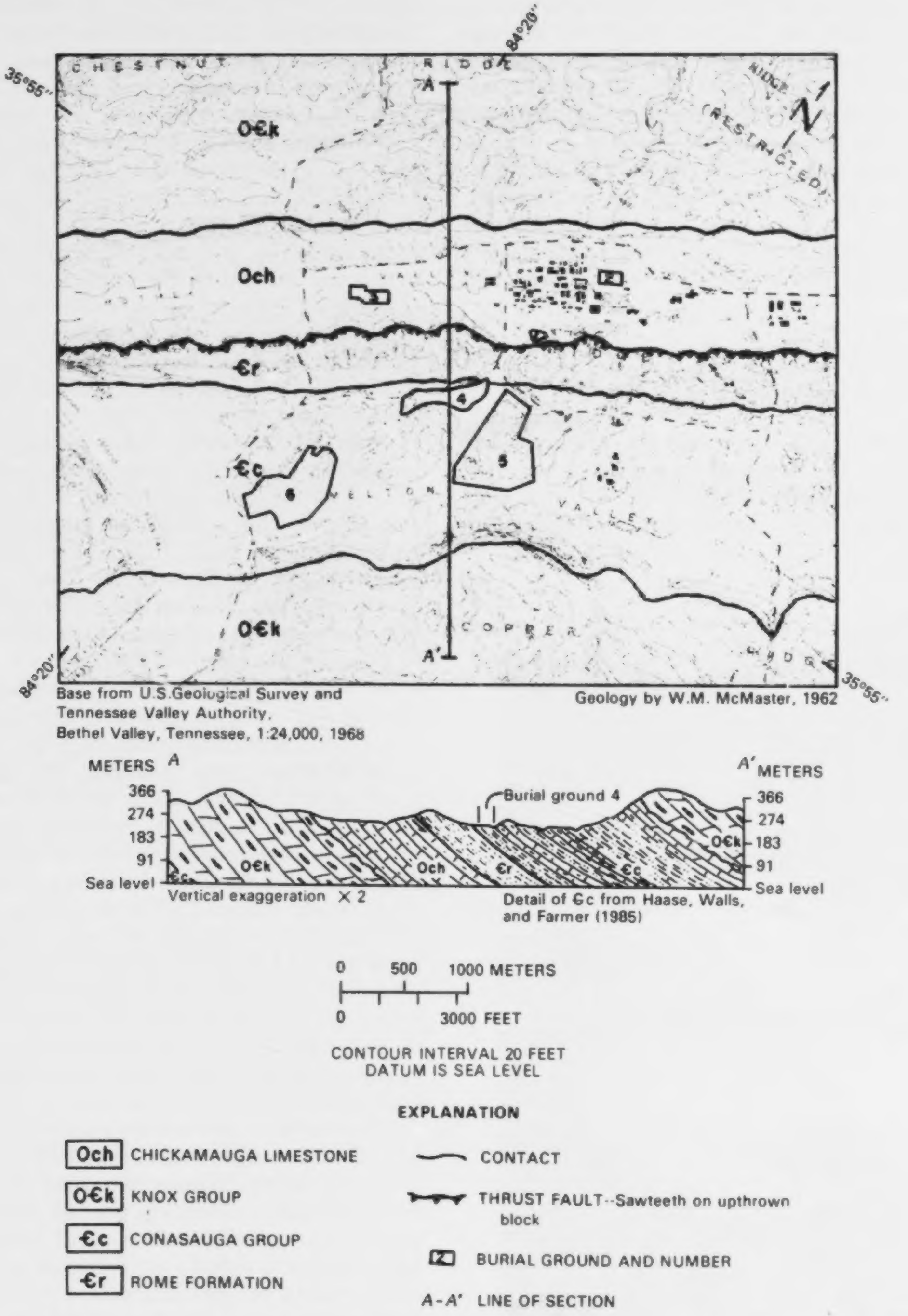
Waste-Burial Procedures

Waste-burial procedures seem to have been relatively simple, even though our knowledge of the procedures at the first four burial grounds is scant. After clearing an area of trees, trenches were excavated to a depth of as much as 4.5 m and to a width of about 3 m. Length of the trenches is variable; the longest trenches, located in burial ground 5, are about 150 m long. Some trenches of other dimensions were excavated to accommodate objects of unusual size. In burial grounds 5 and 6, if not in the earlier burial grounds, an unexcavated area 1 to 1.5 m wide has been left between trenches. The most common orientation of trenches at burial grounds 5 and 6 is downslope. The reason for this alignment has been to minimize the problem of trench walls sloughing into the excavations because, in many areas, the direction of slope is similar to the direction of dip.

Until 1986, the usual procedure was to dump the waste materials into an open trench until the trench was nearly full. The remaining space in trenches containing low-level beta- and gamma-emitting wastes was filled with spoils from the excavation. For many years, trenches with alpha-emitting wastes were covered by about 0.5 m of concrete and then by 0.6 to 0.9 m of spoils. Subsequently, those wastes exceeding 10 Ci/kg of alpha radiation have been placed in retrievable storage rather than being buried at shallow depth. Lined and unlined auger holes have also been used for the burial of certain higher activity wastes. After filling the trenches in a burial ground, the excess spoils were spread over the trenches to dispose of that material and to smooth out irregularities in the terrain. At burial ground 4, after closure, as much as 6 m of permeable construction debris was spread over trenches underlying the northeast end of the burial ground. After the burial grounds were covered with spoils, they were seeded with grass, although in earlier years, when maintenance was minimal, trees were allowed to grow in parts of burial grounds 3 and 5. Unlike some of the commercially operated low-level radioactive-waste repository sites, trench covers were not mounded and monuments were not emplaced to show the ends of the trenches.

Operational procedures at burial ground 6 were modified in 1973 to restrict trenches on sloping terrain to 15.2 m in length, and later, to depths not exceeding that of the water table. In the early 1980's, the procedure for disposing of routine waste contaminated by beta/gamma activity was changed substantially in an effort to provide greater isolation from water. After excavating a trench, open-ended steel cylinders of about 2.8 m in diameter were emplaced upright in them, and an open-ended steel cylinder of slightly smaller diameter was emplaced inside each of the larger cylinders. Concrete was poured across the bottom of the small cylinders to provide a floor and in the space between each concentric pair of cylinders to form a durable structure. Finally, after filling a cylinder with waste, concrete was poured over the waste to fill the void spaces and to provide a cover. A typical trench contains several pairs of cylinders (fig. 8).

Until burial ground 6 was developed, there seems to have been a general disregard of water. At burial ground 3, trenches in the northeastern one-third of the burial ground probably were excavated below the water table, resulting in partial saturation of the waste. At burial ground 4, the trench-filling operation was moved from low ground in summer to higher ground in winter (Lomenick and Cowser, 1961) because of a seasonal rise of the water table into the low-lying trenches. Later, as burial ground 4 was developed, it incorporated three drainages that convey runoff from Haw Ridge to a


84°20''
35°55''
CHESTNUT RIDGE
RIDGE (RESTRICTED)
N
A
OꞒk
Och
Ꞓr
Ꞓc
MELTON
VALLEY
COPPER RIDGE
A'
1
2
3
4
5
6
35°55''
84°20''

Base from U.S.Geological Survey and Tennessee Valley Authority, Bethel Valley, Tennessee, 1:24,000, 1968

Geology by W.M. McMaster, 1962

METERS A
A' METERS
366
274
183
91
Sea level
Burial ground 4
OꞒk
Och
Ꞓr
Ꞓc
Vertical exaggeration × 2

Detail of Ꞓc from Haase, Walls, and Farmer (1985)

0 500 1000 METERS
0 3000 FEET
CONTOUR INTERVAL 20 FEET
DATUM IS SEA LEVEL
EXPLANATION
Och CHICKAMAUGA LIMESTONE
OꞒk KNOX GROUP
Ꞓc CONASAUGA GROUP
Ꞓr ROME FORMATION
CONTACT
THRUST FAULT--Sawteeth on upthrown block
2 BURIAL GROUND AND NUMBER
A-A' LINE OF SECTION

Figure 7. Bedrock geology of the Oak Ridge area, Tenn., and location of burial grounds for low-level radioactive waste at the Oak Ridge National Laboratory, Tenn. Burial grounds 1, 2, and 3 are located in Bethel Valley, which is underlain by the Chicamauga Limestone. Subsequent burial grounds are located in the Melton Valley, which is underlain by the Conasauga group.

tributary of Whiteoak Creek. According to one frequent eyewitness, trenches of this area commonly contained water at the time the waste was buried, apparently owing to the excavation of trenches below the water table. The presence of water was not of concern at that time because the common belief was that the "shale" was not only impermeable, but that it would sorb any radionuclides leached from the waste. Later, as burial ground 5 was developed, trenches in the low-lying areas were excavated to depths below the water table, as also were those at burial ground 6 during the first few years of operation.

Small sections of some trench covers have collapsed into the trenches, exposing the contents and providing direct access to surface runoff and burrowing animals. Such features usually have been repaired with little delay.

Some Results of Waste Burial

At burial ground 3, contaminants are being transported through an integrated cavity system that has developed along the contact between a siltstone and shale unit. As evidence of this, well 41 (fig. 9*A*), which penetrates the cavity system about 120 m east of the burial ground, has become filled to the top of the cavity system with sediment enriched in Cs (fig. 9*B*). Profiles of Sr activity in tributaries of Whiteoak Creek (fig. 9*C*) and Raccoon Creek indicate that this radionuclide is discharged at points close to where the streams intercept the siltstone and shale contact (Steuber and others, 1981). Tracer tests have verified that fluids can traverse the cavity system between the burial ground and the northwest tributary of Whiteoak Creek (about 530 m) in less than 1 day. The ground-water discharge from the cavity system to the northwest tributary was not detected for 30 years because of dilution by a downstream tributary (tributary 10, fig. 9*C*) and because the diluted concentration was masked by the much larger discharges of radioactivity in processing-plant effluents.

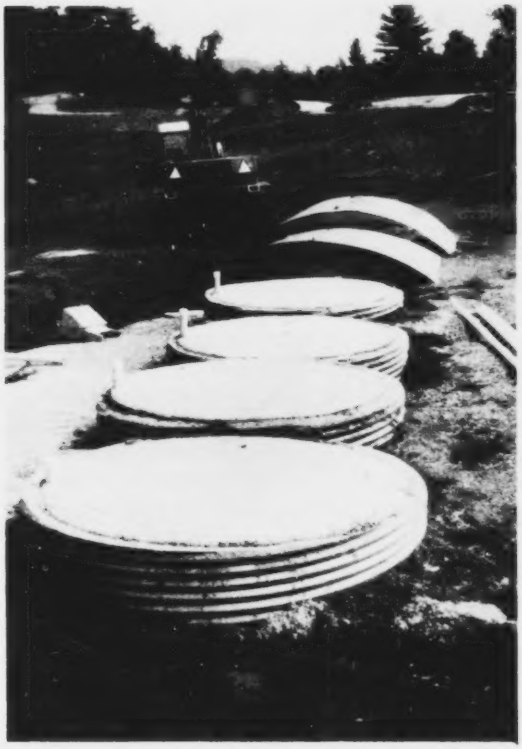


Figure 8. Steel cylinders, used for burial of low-level beta/gamma-contaminated waste, to provide additional isolation of the waste from water.

A greater loss of radionuclides occurs at burial ground 4. The depth to water at the burial ground is shallow (fig. 10), resulting in much of the waste being saturated perennially. Trenches have overflowed (fig. 11), particularly in areas where drainages traverse the site because the rate of recharge has exceeded the rate of discharge through the trench walls. Duguid (1975, 1976) estimated that the discharge of strontium-90 from burial ground 4 ranged from 1.2 to 5.2 Ci annually between 1971 and 1975, and its variability from year to year was directly related to precipitation, indicating transport both in ground water and trench overflow. In a recent study, Huff and Farrow (1983) concluded that trench overflow in the area of burial ground 4 traversed by drainages is now the major mode of strontium-90 transport. Cerling and Spalding (1982), by examining gravel in streambeds in the Whiteoak Creek watershed, determined that the gravel in the tributary along the south side of burial ground 4 had the greatest sustained concentration of strontium-90 of any drainage in the watershed. They also determined that this gravel had minor concentrations of cobalt-60 and cesium-137. In an effort to decrease the discharge of strontium-90, the three drainages crossing burial ground 4 were lined in 1975, but this measure had little effect. In 1983, the drainages were truncated by French drains installed along the north perimeter of the site. After the first 6 months of operation, it was estimated that strontium-90 discharge from burial ground 4 had been decreased by 44 percent (Melroy and Huff, 1985).

At burial ground 5, some of the waste in the lower part of the burial ground is saturated perennially. Long trenches overflow because the orientation downslope directs infiltrated water to the low end where it augments ground water. Overflow from most trenches affected occurs along the regolith-spoils contact and, thus, is not readily visible. Steuber and others (1978) determined that the discharge of ^{90}Sr during 1978 was about 0.45 Ci and was fairly constant from year to year regardless of variability in precipitation; this pattern of discharge indicates that the principal mode of transport is in ground water. A study of gravel in Melton Branch indicated a gradual increase in the concentration of cesium-137 and strontium-90 on the gravel as that stream passed the perimeter of the site; this increase is indicative of contaminated ground water entering the stream at numerous points (Cerling and Spalding, 1982). It is believed that several thousand curies of ^{3}H detected in the drainage annually have come from this burial ground (T.F. Lomenick, Oak Ridge National Laboratory, oral commun., 1974).

The depth to the water table at burial ground 5 has been decreased by waste burial, as it probably has at

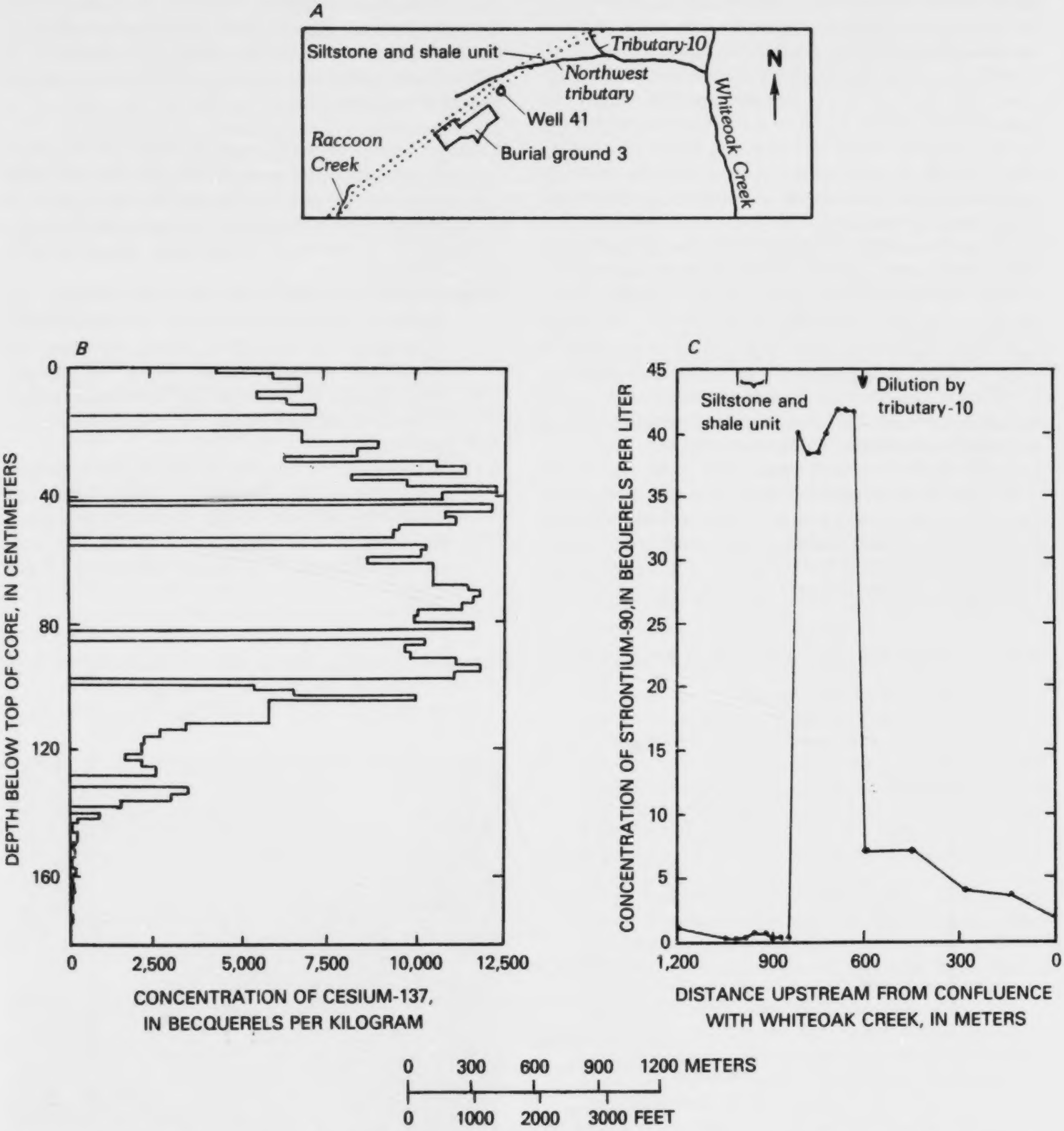


Figure 9. Radionuclide concentrations near burial ground 3, Oak Ridge National Laboratory, Tenn.: *A*, Location map; *B*, Concentration of cesium-137 in core of well 41, October 1980; and *C*, Concentration of strontium-90 in discharge of the northwest tributary of Whiteoak Creek, January 18, 1979.

other burial grounds. The decrease is due to two factors: (1) The additional recharge that infiltrates through the trench covers, which have greater permeability than the undisturbed ground; and (2) the decreased transpiration resulting from replacement of the deep-rooted trees with shallow-rooted grasses. Although the data that indicate ground-water conditions before burial-ground development are few, it appears from preliminary inspection of data that a decrease in the depth to water of 1.8 to 2.7 m has occurred below the south-facing slope.

At burial ground 6 there are few data to demonstrate the lack of waste containment other than the detection of ^{90}Sr on gravel in a short stream within the burial ground (Cerling and Spalding, 1982). Waste containment will be difficult to appraise because contaminants from other sources are in the drainage to the east of the burial ground and in the lake to the south, both of which are projected discharge areas for ground water below this burial ground. Measures have been taken, however, to decrease the potential for transport. These measures include restricting trench length, restricting trench depth, covering some of the disturbed areas with a mixture of spoils and bentonite to minimize infiltration, installing a French drain to dewater some of the early trenches, and, recently, providing greater confinement of the waste in concrete and steel structures.

Through the years, many test wells have been drilled in the burial grounds and in the flow paths from them. The construction characteristics of many test wells permit the ready entrance of surface water and contaminants to the regolith. The design of others permits the unimpeded transfer of water from the regolith to bedrock. Although it is likely that these test wells have had some effect on the hydrology of the burial grounds, that effect has not yet been evaluated.

Lessons Learned

Some of the negative considerations of the ORNL that have become apparent and that may be helpful in developing guidelines for the siting and operation of either future burial grounds at the ORNL or repository sites elsewhere include:

1. Ground-water recharge areas underlain by limestone are unsuitable because of the potential for rapid contaminant transport through solution cavities. In addition, the pathways of transport and discharge points in cavernous media may not be readily predictable.
2. In a humid area with substantial precipitation, the regolith of shale and other materials with negligible permeability is unsuitable, unless, perhaps, the trenches are specially engineered for this environment, because of the propensity for water to collect in trenches, contact waste, and overflow onto the land surface.
3. Geologic media having the lithologic and structural complexity of the Conasauga Group merit low priority for potential burial grounds or repository sites because of the difficulty in defining and proving the pathways of transport and areas of discharge.

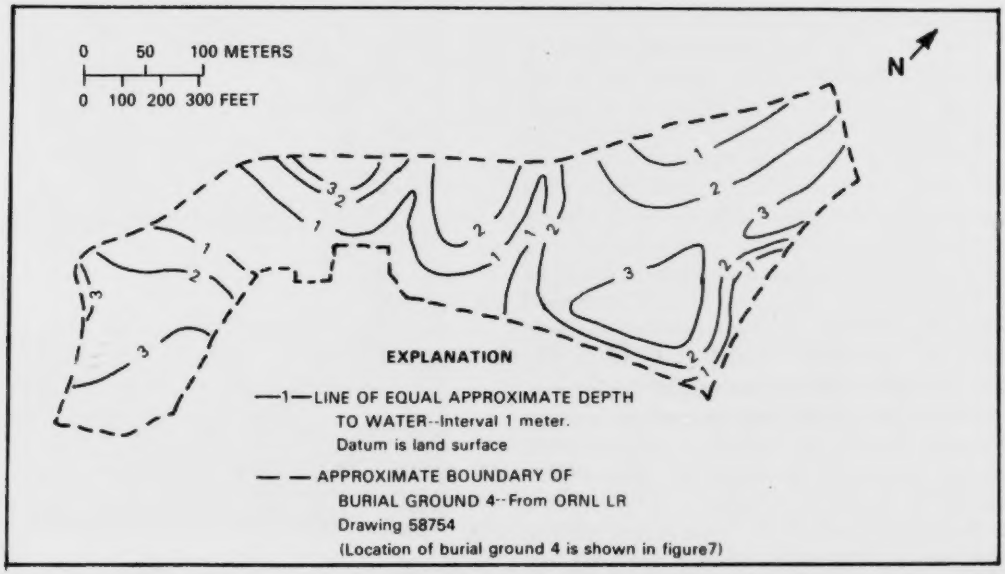

0 50 100 METERS
0 100 200 300 FEET
N
1
2
3
EXPLANATION
—1— LINE OF EQUAL APPROXIMATE DEPTH TO WATER--Interval 1 meter. Datum is land surface
— — APPROXIMATE BOUNDARY OF BURIAL GROUND 4--From ORNL LR Drawing 58754
(Location of burial ground 4 is shown in figure7)

Figure 10. Shallow depth to water at burial ground 4, Oak Ridge National Laboratory, Tenn., June 1, 1978. Much of the waste is saturated perennially.

4. Areas having substantial precipitation and low-permeability media have shallow depths to the water table. Trenches excavated to operational depth and that leave even a 2-m interval between the trench bottom and the water table generally must be close to or within ground-water recharge areas, and this closeness is not desirable because the vertical component of flow then is downward into bedrock, rendering the problem of waste containment and monitoring far more difficult.
5. Areas having substantial precipitation and low permeability media also have many drainages. It is difficult to develop a burial ground or repository site of efficient size without including drainages or being bounded by drainages or both. This has implications pertaining both to the lateral and vertical flow of water and the volume of material available for exchange reactions.

In contrast, some of the positive features of the ORNL are:

1. The regolith of the middle part of the Conasauga Group (interbedded shaley limestone and calcareous siltstone, which are virtually the lower two-thirds of the Maryville Limestone) has a large percentage of clay and silt that has the ability to retard, if not actually stop the transport of many of the biologically hazardous radionuclides as long as they are not in a complexed state. Despite the small particle size, the hydraulic conductivity of the material in many areas is sufficient to cause infiltration to drain from trenches that are above the water table.
2. Frequent precipitation, several tributary drainages, and a major river nearby provide for the dilution of radionuclides discharged to the drainage system.

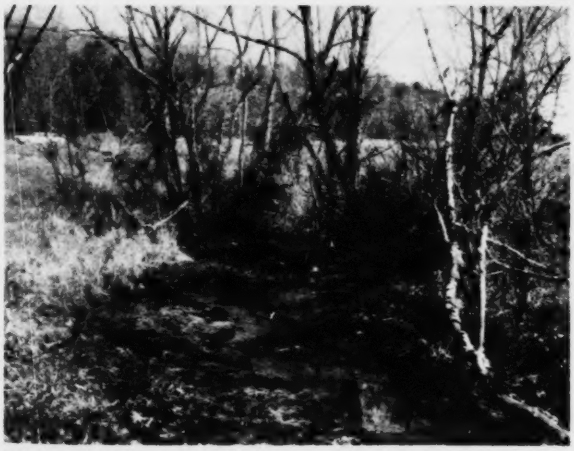


Figure 11. Discharge from trench in burial ground 4, Oak Ridge National Laboratory, Tenn., April, 1974.

Past operational procedures at the ORNL have enhanced the potential for transport. These include the following:

1. Trenches have been excavated with little or no interval between the trench bottom and the water table, particularly the water table that will exist after burial-ground closure and during consecutive years of greater than average precipitation.
2. Trenches in sloping terrain have been excavated to excessive lengths, thereby allowing the overflow of fluids within them.

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Induced Changes in the Hydrology at the Low-Level Radioactive-Waste Burial Grounds near West Valley, New York

By Allan D. Randall

Western New York Nuclear Service Center, which includes two low-level radioactive-waste burial grounds, is located near West Valley in the town of Ashford, Cattaraugus County, about 56 km south of Buffalo in western New York (fig. 12).

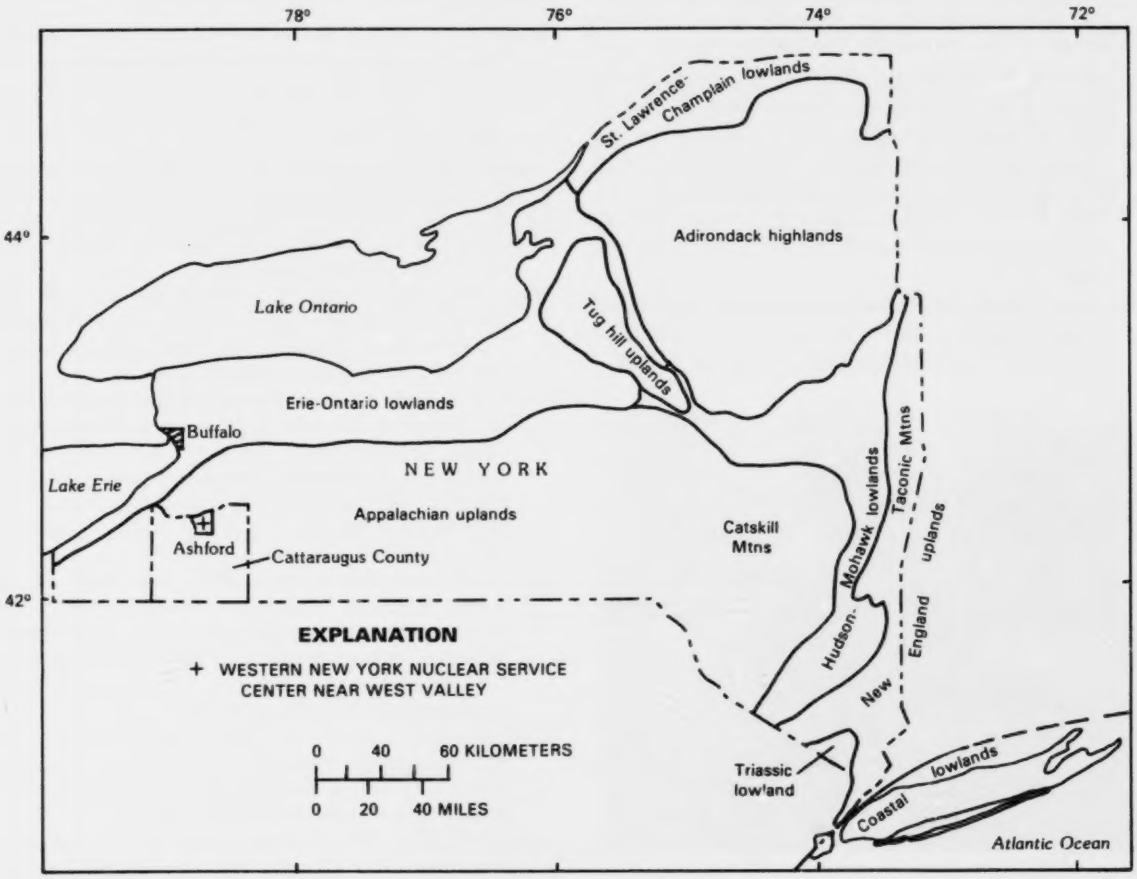

78°
76°
74°
72°
44°
42°
St. Lawrence-Champlain lowlands
Adirondack highlands
Lake Ontario
Tug hill uplands
Erie-Ontario lowlands
Buffalo
NEW YORK
Lake Erie
Appalachian uplands
Ashford
Cattaraugus County
Catskill Mtns
Mohawk lowlands
Hudson-
Taconic Mtns
New England uplands
Triassic lowland
Coastal lowlands
Atlantic Ocean
EXPLANATION
+ WESTERN NEW YORK NUCLEAR SERVICE CENTER NEAR WEST VALLEY
0 40 60 KILOMETERS
0 20 40 MILES

Figure 12. Location of Western New York Nuclear Service Center near West Valley, in the town of Ashford, Cattaraugus County, N.Y., and physiographic regions.

Bedrock in northern Cattaraugus County is a thick sequence of shale with minor siltstone that dips southward at 6 to 8 m/km.

The Service Center is near the northern border of the Appalachian uplands (fig. 12) in an area incised by many major valleys that drained north to the Erie-Ontario lowlands prior to glaciation; these valleys were enlarged and deepened into U-shaped troughs by glacial erosion. These valleys also were repeatedly blocked or ponded as the ice sheet advanced southward (LaFleur, 1979). Consequently, meltwater eroded new valleys southward or westward across former drainage divides. West-flowing Cattaraugus Creek, which drains northern Cattaraugus County, originated in this way. More important from the perspective of waste burial, tongues of ice extended south from the main ice sheet in the valleys; these tongues generally were advancing or retreating through lakes. The result is a thick sequence of fine-grained lake-bottom deposits alternating with clayey till containing substantial reworked lacustrine sediment, with few sand or gravel units. Similar stratigraphy is typical of valleys in the northern part of the Appalachian uplands in New York.

The burial grounds are located in the valley of Buttermilk Creek, on what was the valley floor when the last ice sheet retreated from this valley. Postglacial Buttermilk Creek and its tributaries immediately began to deposit a blanket of 3 to 6 m of gravel and sand across large areas of the valley floor as they reestablished northward flow to Cattaraugus Creek. The fringes of these alluvial deposits barely reached the burial-ground area; most of the land surface at the burial grounds was underlain by till (fig. 13). Within a few thousand years after deglaciation, Cattaraugus Creek adjusted the gradient of its postglacial course and eroded two deep gorges in shale bedrock. As erosion increased in Cattaraugus Creek, it also increased in Buttermilk Creek, which is now incised some 54.5 m below the early postglacial valley floor. Erosion continues along Buttermilk Creek and its tributaries, including Franks Creek, which borders the burial grounds.

A lithologic section across the valley of Buttermilk Creek and through the burial grounds is shown in figure 14. The gravel unit exposed beneath the upper till along Buttermilk Creek is not present beneath the burial grounds. The gravel and the upper part of the unit consisting of lacustrine fine sand, silt, and clay are unsaturated, which is possible because they can drain laterally to the bluff along Buttermilk Creek. The lacustrine fine sand, silt, and clay that becomes finer with depth overlies another till and a still older lake deposit.

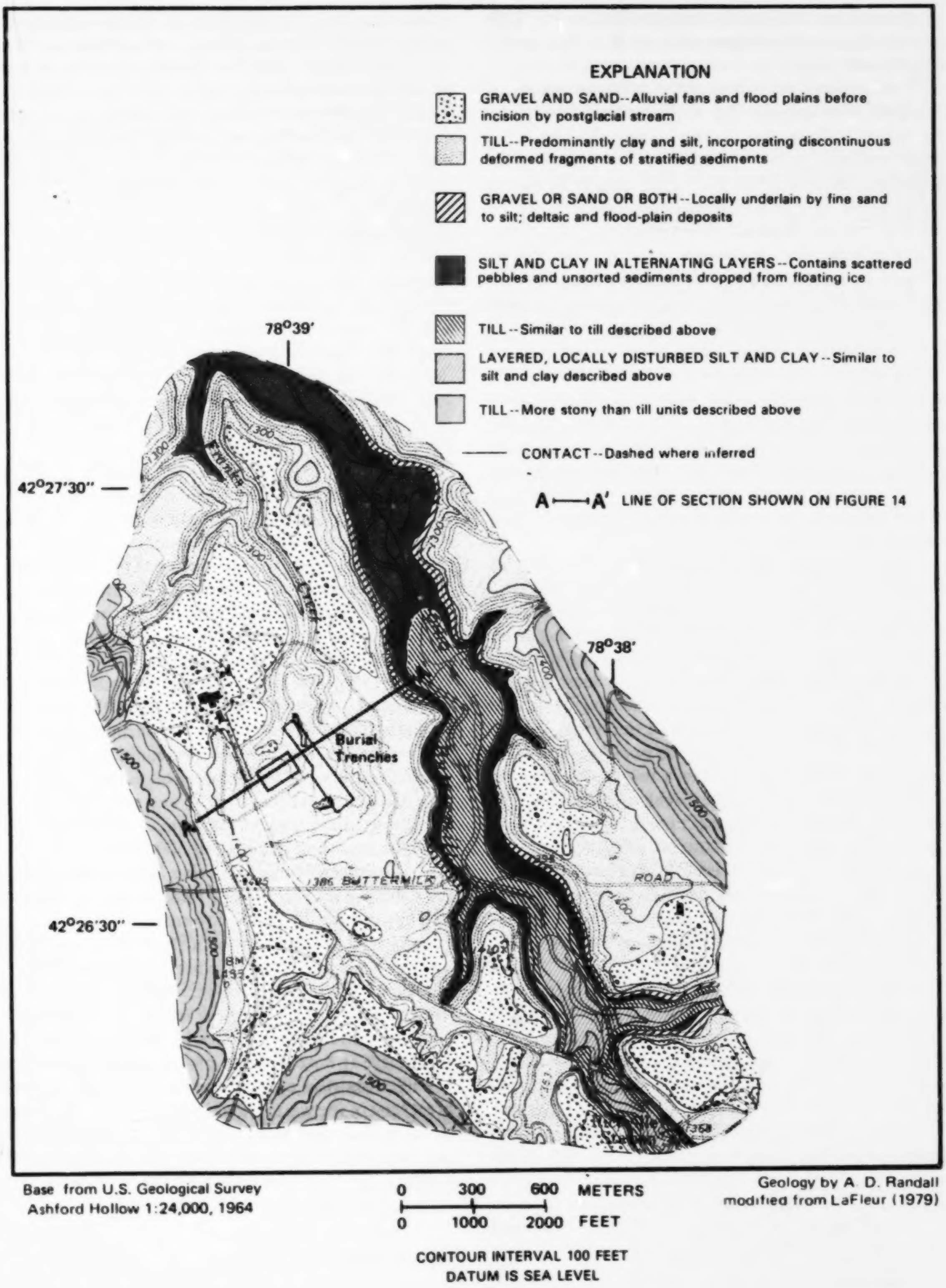
The till at the burial grounds typically is composed of about 50 percent clay, 25 percent silt, and 25 percent sand and gravel. It interfingers randomly with a secondary facies, similar in grain size but containing many tiny blebs and torn deformed wisps of coarse silt only a few millimeters long. Both facies contain randomly oriented pods or lenses of sand, gravel, and alternating silt and clay. Excavations near the burial grounds (including three trenches dug for research by the New York Geological Survey) and test holes consistently demonstrated that these stratified lenses are discontinuous, deformed, and rotated or transported from their point of origin. They are about 7 percent of the till mass, but they do not constitute a continuous layer that might function as a ground-water flow path. The upper 2 to 3 m of the till are oxidized and contain a network of abundant intersecting fractures. Till at greater depth is gray, plastic, and unoxidized, but fractures having firm oxidized borders a few millimeters wide extend downward into the unoxidized till. Fractures decrease in number and width with depth and are absent below 5 m. They may have resulted from dessication during rare extreme droughts. Locally, animal burrows and root casts form avenues for water movement at shallow depths.

Many lithologic sections representing a variety of rocks through the burial grounds have been modeled (Prudic, 1986; Bergeron and others, 1987). All simulations indicate that lateral flow occurs in the upper layers of weathered, fractured, or reworked till, particularly on steep slopes and close to water-filled waste trenches, but that such lateral flow occurs only for short distances and that gradients predominantly are downward, even beneath the valleys of Franks Creek and its tributaries. Prudic (1986) calculated that water would take 300 to 2,300 years to flow downward through the 23 m of till beneath the waste trenches at the burial grounds to the underlying lacustrine silt, then an additional 500 years to flow laterally north-northeast through the silt to Buttermilk Creek. Subsequent work has indicated a slightly steeper gradient toward Buttermilk Creek that would decrease the latter estimate to 300 years.

The steep bluffs bordering Buttermilk Creek and the downstream reaches of Franks Creek are characterized by widespread and obvious mass movement. A layer of soil creep or earthflow about 1 m thick is universally present; rotational blocks are present in many places, and numerous landslides have temporarily dammed small streams and spread colluvial layers of remobilized till onto the flood plains. Studies by Boothroyd and others (1979; 1982) have focused on estimating rates of sediment transport in order to evaluate the risk of eventual breaching of the waste trenches by erosion. Other aspects of the geology and hydrology, briefly summarized above, are discussed in more detail by Dana and others (1979), LaFleur (1979), Albanese and others (1984), Prudic (1986), and Bergeron and others (1987).

Trench Design and History

The Western New York Nuclear Service Center contains two low-level radioactive-waste burial grounds.


EXPLANATION
GRAVEL AND SAND--Alluvial fans and flood plains before incision by postglacial stream
TILL--Predominantly clay and silt, incorporating discontinuous deformed fragments of stratified sediments
GRAVEL OR SAND OR BOTH--Locally underlain by fine sand to silt; deltaic and flood-plain deposits
SILT AND CLAY IN ALTERNATING LAYERS--Contains scattered pebbles and unsorted sediments dropped from floating ice
TILL--Similar to till described above
LAYERED, LOCALLY DISTURBED SILT AND CLAY--Similar to silt and clay described above
TILL--More stony than till units described above
CONTACT--Dashed where inferred
A——A' LINE OF SECTION SHOWN ON FIGURE 14
78°39'
78°38'
42°27'30"
42°26'30"
Franks
Creek
Burial Trenches
BUTTERMILK
ROAD
1300
1400
1500
A
A'
0 300 600 METERS
0 1000 2000 FEET
CONTOUR INTERVAL 100 FEET
DATUM IS SEA LEVEL

Base from U.S. Geological Survey
Ashford Hollow 1:24,000, 1964

Geology by A. D. Randall
modified from LaFleur (1979)

Figure 13. Surficial geology of area where low-level radioactive-waste burial grounds are located in the valley of Buttermilk Creek, near West Valley, N.Y.

The larger of the two is a State-licensed burial ground for commercial waste. When this burial ground was opened in 1963, some 25 trenches were envisioned, but burial was suspended in 1975 after 14 trenches had been filled. Most of the trenches are about 180 m long. Each is nominally 6 m deep, 6 m wide at the bottom, and 11 m wide at the top. Each was nominally separated from the adjacent trench by 2 to 3 m of undisturbed till (Kelleher, 1979), although parts of the side walls collapsed many times, resulting in more variable separations, additions of backfill, and nonuse of parts of some trenches. The trenches were excavated in segments, 15 to 30 m at a time, sloped at a nominal 2 percent grade from one end to the other to provide drainage. They were excavated by bulldozer, so both ends were gently sloped to provide access. A gravel-filled sump was constructed, generally near the low end, in which a vertical 20-cm-diameter riser pipe was installed for monitoring water levels and for pumping out water if necessary. The till removed in excavating the trench was stockpiled and later used to cover the waste; it was graded to keep runoff out of the open trench prior to closure, and later was compacted and graded to its final form.

The potential for accumulation of water in the trenches was recognized from the start (Kelleher, 1979) and did in fact occur. In trenches 3, 4, and 5, completed by 1969, water levels rose above the top of the undisturbed till into the cover by 1975. Small seepages to land surface were noted in March 1975. Beginning in 1975 and continuing through 1983, water levels in several trenches were lowered by periodic pumping and the water treated to remove all isotopes other than tritium before release to Franks Creek.

Trench design was revised several times in an effort to eliminate this accumulation of water:

1. Trenches 1 through 4 initially were covered by a single mound, but in 1968 individual mounds were shaped over each trench.

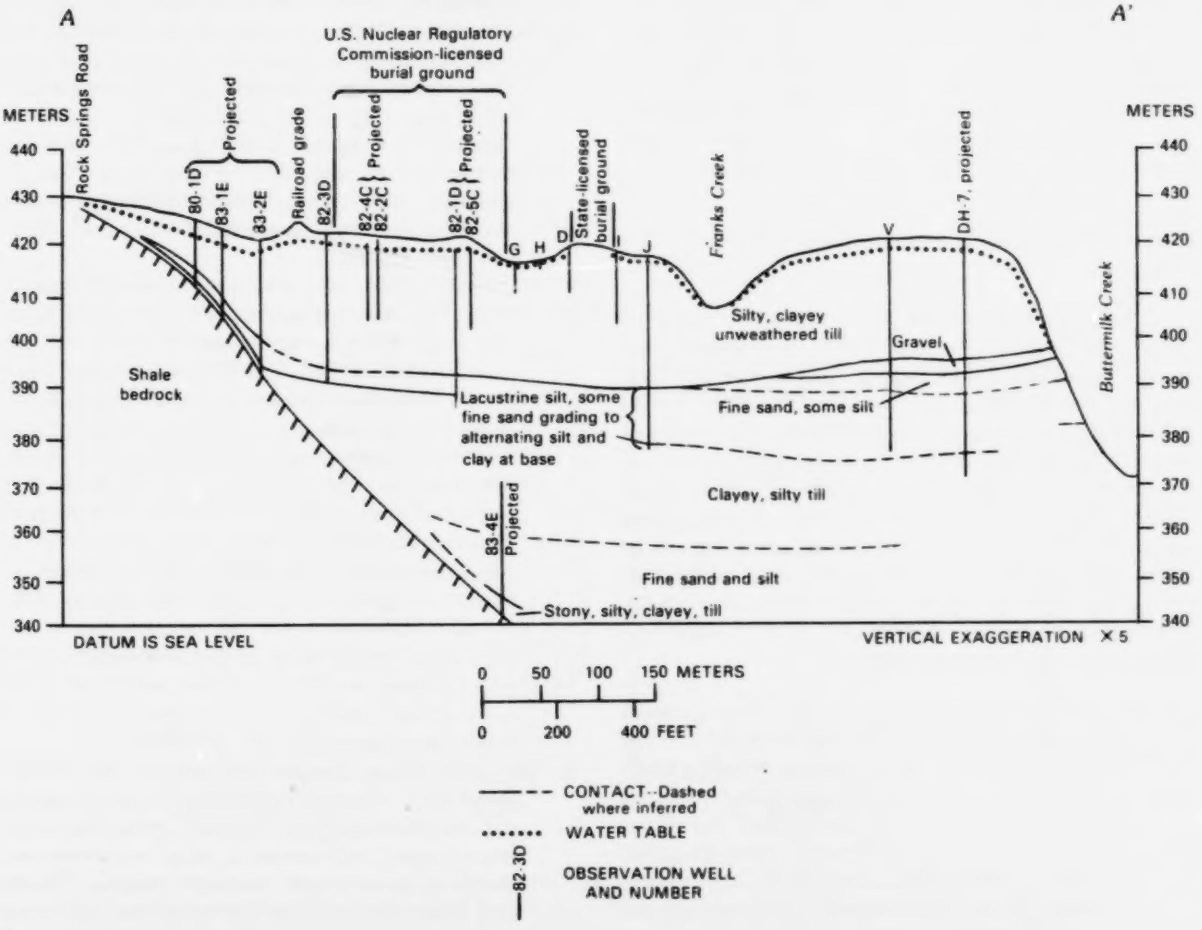

A
A'
U.S. Nuclear Regulatory Commission-licensed burial ground
METERS
440
430
420
410
400
390
380
370
360
350
340
Rock Springs Road
80-1D
83-1E
83-2E
Projected
Railroad grade
82-3D
82-4C
82-2C
Projected
82-1D
82-5C
Projected
G
H
D
State-licensed burial ground
I
J
Franks Creek
V
DH-7, projected
Buttermilk Creek
Shale bedrock
Silty, clayey unweathered till
Gravel
Fine sand, some silt
Lacustrine silt, some fine sand grading to alternating silt and clay at base
Clayey, silty till
83-4E
Projected
Fine sand and silt
Stony, silty, clayey, till
DATUM IS SEA LEVEL
VERTICAL EXAGGERATION × 5
0
50
100
150 METERS
0
200
400 FEET
CONTACT--Dashed where inferred
WATER TABLE
82-3D
OBSERVATION WELL AND NUMBER

Figure 14. Lithologic section across the valley of Buttermilk Creek and through the burial grounds near West Valley, N.Y. (modified from Bergeron and Bugliosi, 1987).

2. Also in 1968, the specifications for future trenches were changed to increase cover from 1.2 m to a minimum of 2.4 m, require separation of 3 m between trenches, impose a surcharge load by temporarily piling spoil from each new trench atop the previously completed trench (a practice not consistently followed previously), and grade land surface to drain water away from the trenches.
3. In 1978, an additional 1.2 m of reworked till cover was added to the older trenches, and in 1980 the top 0.7 m of cover over the newer trenches was replaced and recompacted.

The Nuclear Regulatory Commission-licensed burial ground is a 2.2-ha area used from 1966 through 1972 for disposal of radioactive waste generated by operation of a nuclear-fuel reprocessing plant, including spent fuel hulls, fuel-assembly hardware, failed process vessels and equipment, degraded process solvent, packaged laboratory waste, ventilation filters, and miscellaneous debris. From 1975 through 1981, this burial ground received waste generated by maintenance, decontamination, and decommissioning of the reprocessing plant. This burial ground contains about 210 small trenches and pits 1 to 30 m long and 3 to 15 m deep. Few details as to trench and pit construction are available; most were excavated and not lined, but a few have steel liners with cement-grouted gravel at the bottom.

Effects of Site Operation on Hydrology Infiltration through Reworked Till

Infiltration of precipitation through the reworked till used to cover excavations at the burial grounds has exceeded downward flow through the in-place unweathered till beneath the excavations, resulting in gradual or episodically rising water levels in many burial trenches or pits. Infiltration has taken place primarily via cracks in the trench covers that form as a result of surface desiccation in dry weather and subsurface collapse of decaying waste. The cracks also function as conduits to the atmosphere for gas generated by organic and radiometric decay. The effect of water and gas transfer through the trench covers has been established beyond question by a variety of evidence. For example:

1. Lateral ground-water seepage could not have caused the rising water levels observed during 1972–79 in the trenches at the State-licensed burial ground. Piezometers near the trenches consistently verified ground-water gradients to be outward and downward from the trenches (Prudic, 1986; Bergeron and others, 1987). Water levels in the inner trenches were at times higher than those in the outermost trenches, and these water levels were rising rapidly.
2. The number, size, pattern, and persistence from year to year of fractures on the excavated trench surfaces indicated they were deep-seated features that might transmit water (Dana and others, 1979; Prudic, 1986, p. 54). Most cracks were unrecognizable in winter, but reappeared in the same position each summer, indicating permanent lines of weakness. Subcircular depressions surrounded by concentric cracks also were observed; they indicated collapse of buried waste.
3. Several types of evidence indicate that these cracks were indeed avenues of rapid water inflow to the trenches. On two occasions, large volumes of water were poured into cracks and disappeared without a trace. Continuous records of water levels in trenches had, at times, a steplike pattern of rapid rises (fig. 15) that coincided with precipitation. Filling of a subsidence hole in April 1979 abruptly ended an episode of rapid, stepwise water-level rises in trench 12 (Prudic, 1986, p. 51). The response of trench-gas pressures to barometric-pressure fluctuations was more rapid in trenches with a history of rapidly rising water levels (Prudic, 1980) and was much more rapid in summer, when cracks were obviously enlarged, than in winter or spring. Water levels began to rise rapidly and persistently in trenches 3 through 5 in late 1971 and in trenches 11 through 14 in late 1978, in each case after an unusually dry summer when desiccation cracks may have penetrated more deeply than usual (Prudic, 1986, fig. 23).
4. Matuszek (1980) estimated annual gas production from seven trenches studied to be about 24,000 m^3 and noted that the continuous production of gas would tend to lift and rupture trench covers if some means of venting were not available. Breaks in the sump riser pipes may provide this venting in some trenches, in addition to cracks in the trench covers. The total area of cracks may be approximately estimated from opening and closing vent pipes in each trench and by noting any change in the rate at which gas pressure within the trench equilibrates to barometric pressure (fig. 16). Data presented by Lu and Matuszek (1979) allow estimates of less than 1 cm^2 for the total area of cracks for each of two trenches in February and April 1978 but indicate that crack areas are as much as 30 times larger in summer than in early 1978.
5. The small burial trenches and pits in the Nuclear Regulatory Commission-licensed burial ground at the Western New York Nuclear Service Center are not equipped with sumps or wells in which water levels can be measured. However, there is evidence that infiltration through the trench and pit covers also has allowed a rise of water levels. In 1983,

kerosene and tributylphosphate (TBP), both organic solvents, were detected in water from a shallow observation well 6 m north of the burial ground. Subsequently, kerosene was detected in water from shallow observation wells mostly at depths of 3 to 4 m (Bergeron and others, 1987). Clearly, kerosene escaping from ruptured containers in a nearby burial pit could not have migrated outward at this depth until it had floated upward atop water accumulating in the pit. Another observation-well cluster, 9 m north of the burial ground, penetrated backfill to a depth of 3.5 m. A water-yielding zone at the base of the backfill had an unusually high-pressure head of about 3 m, and pressure heads increased toward the burial ground (Bergeron and others, 1987). The backfill resulted from construction of a ramp required to emplace a heavy tank in a burial pit. The high-pressure heads in the pit cover here, where there is no buried waste that could collapse to cause cracks, indicate either that the infiltration capacity of reworked till is greater than in-place till even in the absence of collapse, or that rapid percolation of precipitation into burial trenches and pits has created a groundwater mound within the burial ground that is expanding outward. The small size of many of the trenches and pits at the burial ground probably made it difficult to compact the cover material as effectively as at the State-licensed burial ground; this would favor infiltration at the smaller sized trenches and pits (Nicholson and Hurt, 1985).

6. The covers over the older trenches at the State-licensed burial ground were reconstructed in 1978 in order to decrease infiltration of water. The existing material was recompacted with heavy machinery and another 1.3 m of till added. Prudic (1986) reported that the rise in water level in 1979 in all these trenches was only 15 percent of that in 1978, which indicates that the reconstruction was effective. Reconstruction of the newer trenches took place in 1980. According to Daniel Anderson (New York Energy Research and Development Authority, oral commun., 1987), infiltration has been substantially decreased except in trench 14, but it has not been eliminated. However, this type of reconstruction may only delay or repair the effects of waste decay, cover collapse, crack development, and precipitation infiltration. Matuszek and Robinson (1983) and Matuszek (1986) argued that only incineration of waste would yield a prod-

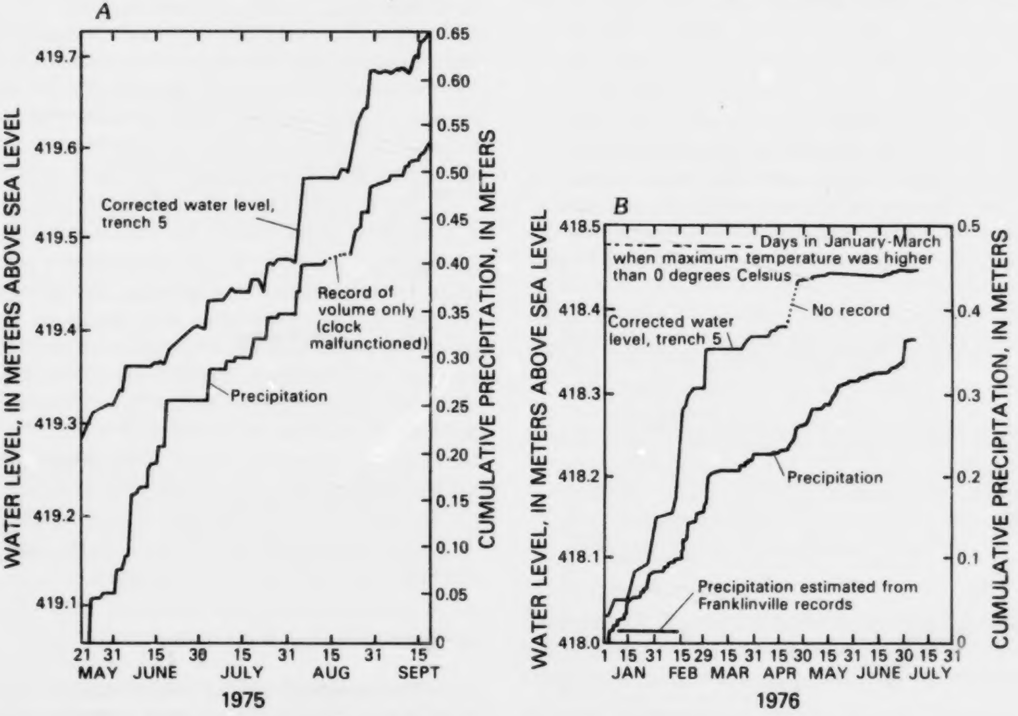


Figure 15. Water level in trench 5 in relation to precipitation at burial grounds near West Valley, N.Y.; hydrograph of water level corrected to remove effects of barometric fluctuations: *A*, May through September, 1975 (modified from Prudic and Randall, 1979); and *B*, January through July 1976. The steplike pattern of rapid rises coincided with precipitation.

uct that could be buried without the prospect of collapse. An innovative technique of trench- and pit-cover construction has been implemented recently by the West Valley Nuclear Services Company for the smaller burial trenches and pits at the Nuclear Regulatory Commission-licensed burial ground. This technique incorporates grids of interlocking plastic strips within the trench or pit cover and bentonite walls around the edge, in the hope that collapse of the buried waste will result in the cover settling as a coherent plug (R.R. Blickwedehl, West Valley Nuclear Services Company, written commun., 1987).

Effect of Regrading the Land Surface on Infiltration

The construction and operation of the two burial grounds have involved considerable regrading of the land surface, chiefly for two purposes: (1) To provide reasonably level working areas for vehicles and equipment; and (2) to ensure runoff of surface water without appreciable erosion. Several hydrologic observations have been interpreted to indicate that such regrading can markedly affect infiltration rates. The evidence is not entirely convincing, but it deserves serious consideration.

Prudic (1986) and Bergeron and Bugliosi (1987) have reported that pressure heads within the till generally are less than 4 m, and that where pressure heads are relatively large (or small) at shallow depth, they tend to be similarly large (or small) at greater depths. At some sites, only negative pressure heads (dry piezometers) were recorded during the studies. The investigators inferred that pressure heads generally were caused by localized variations in infiltration, which was minimal in areas where the natural soil had been removed and the land surface graded to a smooth slope that drained water quickly.

After the recompaction of trench covers in 1978–80, water levels have risen only slightly in most trenches. In trench 14, the latest and westernmost of the south trenches, however, water levels rose 2.5 cm or 5 cm/mo from January through June 1984, December 1984 through May 1985, and (on the average) December 1985 through May 1986. In June, July, and August 1986, rises of 10 to 25 cm/mo were recorded, prompting renewed investigation (Daniel Anderson, New York Energy Research and Development Authority, written commun., 1987). Examination of trench cover disclosed no obvious subsidence or unusual cracks that might explain the sudden increase in rate of water-level rise. Examination of the area, however, disclosed that a culvert on a shallow drainage ditch west of the burial ground was plugged, allowing runoff from a substantial area outside the burial ground to flow across the field immediately west of trench 14 during intense storms. In June and July 1986, rainfall ranging from 25 to 75 mm was measured on seven dates. Once an observer reported several centimeters of water in the field.

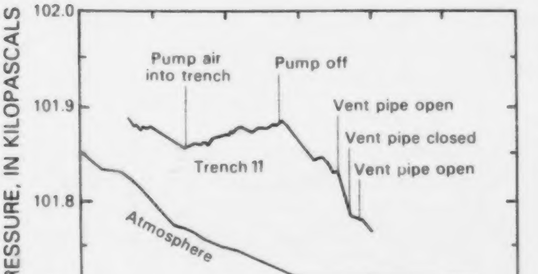


Figure 16. Pressure changes in trench 11 and atmosphere, February 9, 1978, at burial grounds near West Valley, N.Y. (modified from Lu and Matuszek, 1979).

On August 13, 1986, the culvert was removed and the perimeter ditch regraded to prevent surface runoff from entering the fenced area, and the field west of trench 14 was cleaned off and graded to enable more rapid runoff. Thereafter, water levels rose only slightly, despite several storms with more than 25 mm of rainfall.

Several closely spaced test holes were augered in the field west of trench 14 near its south end. Some of these holes penetrated through 0.17 to 2 m of fill into a lens of gravel, sand, and organic silt with shells. The lens dips toward trench 14 and probably is alluvium along the natural channel of the small stream that had been diverted to the perimeter drainage ditch. Water is thought to have flowed along this lens into the trench.

The regrading of land surface also has contributed in small ways to increasing the risk of erosion—to what some have referred to as the environment encroaching on the burial ground. The regrading of land surface prior to construction of trenches 1–5 seems to have piled additional material at the crest of the slope northwest of trenches 3–5 (Kelleher, 1979; Prudic, 1986, fig. 20); this could favor slope failure. Slump scars at the crest of this slope were mapped by Dana and others (1979). The draining of a natural depression immediately north of the Nuclear Regulatory Commission-licensed burial ground has resulted in a gully (Bergeron and others, 1987, fig. 16; Kappel and Harding, 1987, p. 11), the rapid incision of which has been a matter of concern.

Lessons Learned at West Valley

The investigators who studied the burial grounds at West Valley cited in this paper generally have determined that radioisotope transport by ground water has been and is likely to remain negligible. Migration of radioisotopes to land surface may take place in these ways: (1) By flow of water through backfill or perhaps through near-surface fractured till if renewed or continuing infiltration through the trench covers causes water levels to rise above or within 1 or 2 m of the land surface; (2) by gas transport through the trench or pit covers; or (3) perhaps by slope failure, after many years, if incision of Franks Creek is not controlled.

There is no reason to believe that percolation into or through the pre-1986 trenches or pits can be decreased to natural rates without periodic maintenance as long as collapse of buried waste continues.

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Results of Recent Geohydrologic Studies at the Maxey Flats Low-Level Radioactive-Waste Disposal Site, Fleming County, Kentucky

By Mark A. Lyverse

Introduction

The Maxey Flats low-level radioactive-waste disposal site, hereafter referred to as the Maxey Flats site, was operated as a shallow-land burial site for low-level radioactive waste for 15 years (1963–77). The site is owned by the Commonwealth of Kentucky; remedial work and custodial activities are the responsibility of the Kentucky Natural Resources and Environmental Protection Cabinet. The site was licensed to receive low-level radioactive waste generated by industry and Federal agencies, including the U.S. Department of Defense. In 1977, radionuclides were detected migrating from a closed disposal trench into an adjacent, newly constructed trench. This discovery heightened concern by the Commonwealth that radionuclides may be migrating from the repository site and prompted closure of the site. The repository site now is included in the U.S. Environmental Protection Agency's list of hazardous-waste sites requiring priority remedial action.

The Maxey Flats site is located on a dissected plateau in the Appalachian foothills region of east-central Kentucky. The site is in Fleming County, about 14.5 km north of Morehead. The Commonwealth owns 113 ha of land; 17 ha (fig. 17) are designated as restricted and controlled for the purpose of radiation protection.

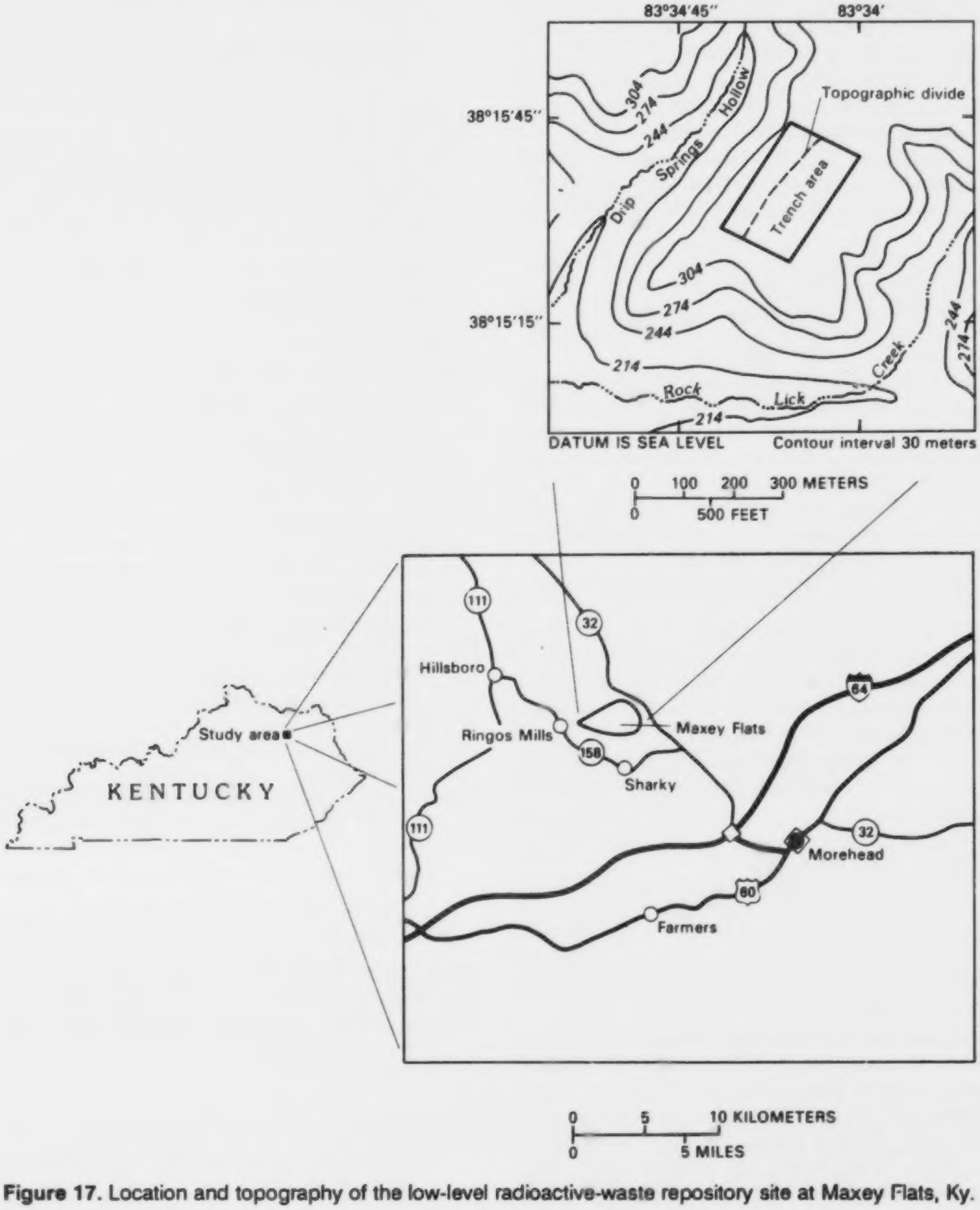
83°34'45"
83°34'
38°15'45"
38°15'15"
Topographic divide
Trench area
Drip Springs Hollow
Rock Lick Creek
304
274
244
214
DATUM IS SEA LEVEL
Contour interval 30 meters
0 100 200 300 METERS
0 500 FEET
111
32
Hillsboro
Ringos Mills
158
Sharky
Maxey Flats
64
Morehead
60
Farmers
Study area
KENTUCKY
0 5 10 KILOMETERS
0 5 MILES

Figure 17. Location and topography of the low-level radioactive-waste repository site at Maxey Flats, Ky.

Within the restricted area, 10 ha have been used for the burial of low-level radioactive wastes. At the present time (1987), most of the 10 ha are covered with a 0.38- to 0.51-mm-thick polyvinylchloride (PVC) membrane cover. This cover is designed to decrease infiltration of precipitation into the closed burial trenches.

This paper is primarily concerned with U.S. Geological Survey studies at the Maxey Flats sites during 1985–87. These studies included: subsurface movement of tritiated water from the trenches; effectiveness of the PVC cover for limiting infiltration into the burial trenches; and preliminary results from a study concerned with quantifying hillslope erosional rates from the relatively steep hillsides surrounding the disposal site. Also, this paper will briefly describe the general site geohydrology with special emphasis on the regolith host media and previous disposal activities such as trench design and construction.

Site Geohydrology

The Maxey Flats site is underlain by gently dipping (4.7 m/km) Silurian, Devonian, and Mississippian rocks consisting chiefly of fissile carbonaceous shale, clay shale, and some siltstone and sandstone. Listed in order of decreasing age, the rocks comprise the following formations: upper part of the Crab Orchard Group (23 to 43 m thick) of Silurian age; Ohio Shale (46 to 76 m thick) of Devonian age; Bedford Shale (3 to 12 m thick) of Mississippian and Devonian age; Sunbury Shale (4 to 6 m thick) of Mississippian age; and the Farmers Member (including the Henley Bed) (10 to 300 m thick) and the Nancy Member (46 to 60 m thick) of the Borden Formation, both of Mississippian age (fig. 18).

At the repository site, only the lower 12 to 15 m of the Nancy Member is present. The hydrologic characteristics of the Nancy Member are of particular importance because all burial trenches were constructed in the regolith of this member and most problems, such as water accumulation in trenches and the lateral subsurface migration of leachate from the trenches, occur in this member. Below the Farmers Member, chloride concentrations generally increase with depth, indicating the most active part of the ground-water system is in the upper part of the hill. However, all rocks in the area are fractured to some extent; the upper rocks in particular

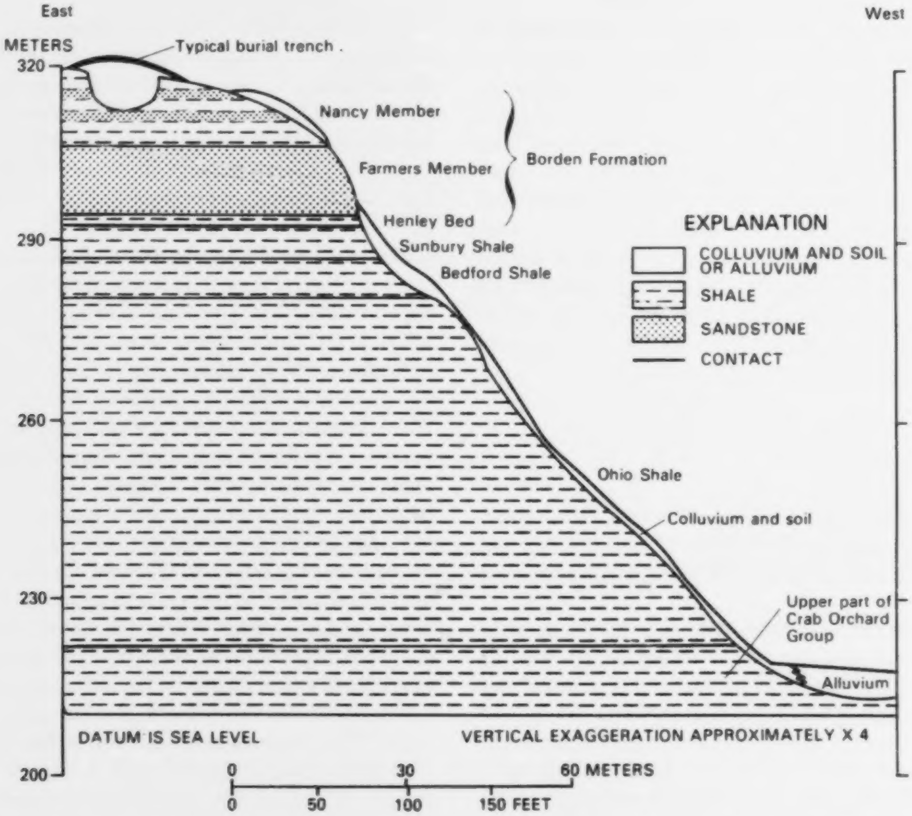
East
West
METERS
320
290
260
230
200
Typical burial trench
Nancy Member
Farmers Member
Borden Formation
Henley Bed
Sunbury Shale
Bedford Shale
Ohio Shale
Colluvium and soil
Upper part of Crab Orchard Group
Alluvium
EXPLANATION
COLLUVIUM AND SOIL OR ALLUVIUM
SHALE
SANDSTONE
CONTACT
DATUM IS SEA LEVEL
VERTICAL EXAGGERATION APPROXIMATELY X 4
0
30
60 METERS
0
50
100
150 FEET

Figure 18. Geologic section through part of the hill on which the low-level radioactive-waste repository site at Maxey Flats, Ky. is located. At the repository site, all trenches are constructed in the Nancy Member.

have brown, iron-stained alteration bands that are attributed to weathering along planes of water movement.

The weathered Nancy Member forms the regolith in the Maxey Flats area. Two sandstone beds were mapped in the regolith by McDowell and others (1971). They are very fine grained silty sandstones in some areas but are siltstone in others. The upper part of the Nancy Member on the repository site weathers to form a yellow-brown regolith, which extends at least to the depth of the upper sandstone bed. In places, the shale between the two sandstone beds is only partially weathered and is mottled yellow brown and gray. Where the sandstone beds are absent, weathering extends to greater depths. The thickness of the regolith ranges from a few centimeters to about 8 m at the site (Zehner, 1983). The upper sandstone bed is at about the middle of the regolith; the lower sandstone bed is at the base of the regolith. The two beds are absent locally, owing to nondeposition or erosion, but both are present throughout most of the Maxey Flats site. Water movement through the sandstone beds primarily is through fractures. Fractures in both beds generally are present in sets and typically have a vertical or almost vertical orientation. These competent strata are interbedded with clay and shale that have minimal vertical and horizontal permeability.

The significance of the upper and lower sandstone beds to ground-water recharge and discharge became more apparent than previous studies had indicated when 68 wells were installed in 1985 (fig. 19). These wells were drilled into the Nancy Member within the restricted area and around the periphery of the area. The sandstone beds are greatly variable in occurrence, thickness, and number and orientation of fractures. The upper sandstone bed generally is above the level of most buried waste and, therefore, does not affect lateral movement of leachate. The lower sandstone is at the level of buried waste in most trenches and appears to control some movement of leachate from the trenches.

Trench Design, Construction, and Brief Operation History

More detailed descriptions of waste form, waste burial method, and concentration of radioactivity are described in Zehner (1983), from which the following is largely taken.

Most trenches are about 100 m long, 17 m wide, and about 7 to 8 m deep. Waste was dumped into the open trenches, and the top of the waste was covered with regolith as the trench was progressively filled. A clay and crushed shale cover at least 1 m thick covers the trenches. PVC covers were emplaced over trenches beginning in the autumn of 1981. The covers were installed to inhibit vertical infiltration and to minimize collection of water in the trenches to prevent the so-called bathtub effect. Each trench is equipped with several sumps for the collection and removal of leachate. Effectiveness of this PVC cover will be described in a later section.

Disposal of wastes began in May 1963. At the time of official closure in 1977, the site contained about 36,000 m^3 of waste, which included about 700,000 ci of tritium. Most of the waste was buried in solid form, except for the tritium, which typically was buried as tritiated water enclosed in glass containers and packed in steel drums. Many containers were broken by dumping the waste into open trenches, by compaction during emplacement of the trench cover, and subsequently by corrosion and decay. These processes probably facilitate leaching and release of tritiated water in burial trenches and eventually into the fractured rocks that form the walls and bottoms of the burial trenches. Because tritiated water leaks from the site, much of the monitoring effort at the site today (1987) focuses on determining the occurrence, rate of movement, and extent of tritiated-water migration. Other radionuclides have been detected in water from monitoring wells, but only at concentrations slightly greater than background concentrations.

Ground-Water Flow and Tritium Movement through Regolith

Recent studies have substantiated what earlier investigators suspected. That is, the upper part of the ground-water system is where most ground-water flow and radionuclide movement occurs. These recent studies have verified that contaminated water has migrated from the burial grounds through the fractured lower sandstone bed. Water containing tritium concentrations of as much as 3.5 mCi/mL has been sampled from wells yielding water from the lower sandstone bed as much as 70 m from the burial area. The lower sandstone bed ranges in depth from about 5 to 7 m below the land surface and formed the bottom for most trenches during burial operations. This bed appears to have more open joints and fractures than the overlying and underlying shale. These joints and fractures are conduits for water moving from the topographically higher burial trenches to downslope observation wells. Through 1986, the migration of large concentrations of tritium seemed to be confined to the area in the northwestern part of the site (fig. 19). Movement of leachate in this area seems to be controlled by the gradient, thickness, and number of fractures in the lower sandstone bed. Where the lower sandstone bed is absent, the surrounding shale tends to impede movement of tritiated water. Some of the migrating tritiated water may move to lower rock units; some water moves to the edge of the plateau and into the colluvium. The water then flows downslope through the shallow subsurface regime and becomes partially transpired (seasonally) through trees and vegetation on surrounding hillslopes. Wet-weather seeps have been observed on surrounding hillsides, and water sampled from such seeps below the outcrop of the lower sandstone bed contained tritium concentrations of as much as 2,500 mCi/mL (Doyle Mills, Kentucky Department for Environmental Protection, oral commun., 1987). The seeps generally flow after snowmelt and rainfall and generally cease flowing as plant transpiration increases in the late spring and summer.

Rate of radionuclide movement through the lower sandstone bed has been estimated from onsite data at only one area of the burial site. This estimate, using migration rates of Co and Mn, was made in the southeast corner. Zehner (1983) reported that these two radionuclides were detected by site personnel in water from the lower sandstone bed within an empty trench. The effective velocity for these radionuclides was estimated to be about 17 m/yr; the Co and Mn presumedly had migrated from a nearby covered trench.

Velocity estimates for flow through the lower sandstone bed currently (1987) are underway in the northwest part of the site. Three inorganic tracers (chloride, bromide, and iodide) and one organic tracer (rhodamine WT) were placed in one contaminated observation well in mid-January 1987. Ten other observation wells were drilled radially around the injection well for rate-of-movement monitoring. As of May 1987, no tracer had been detected in water from any of the observations wells that are 2 to 7 m away from the injection well.

Effectiveness of PVC Cover for Limiting Infiltration

In 1981, an evaluation of the water-management program at the site was made by the Commonwealth, and a revised site-management plan was developed. An objective of this revised site-management plan was to

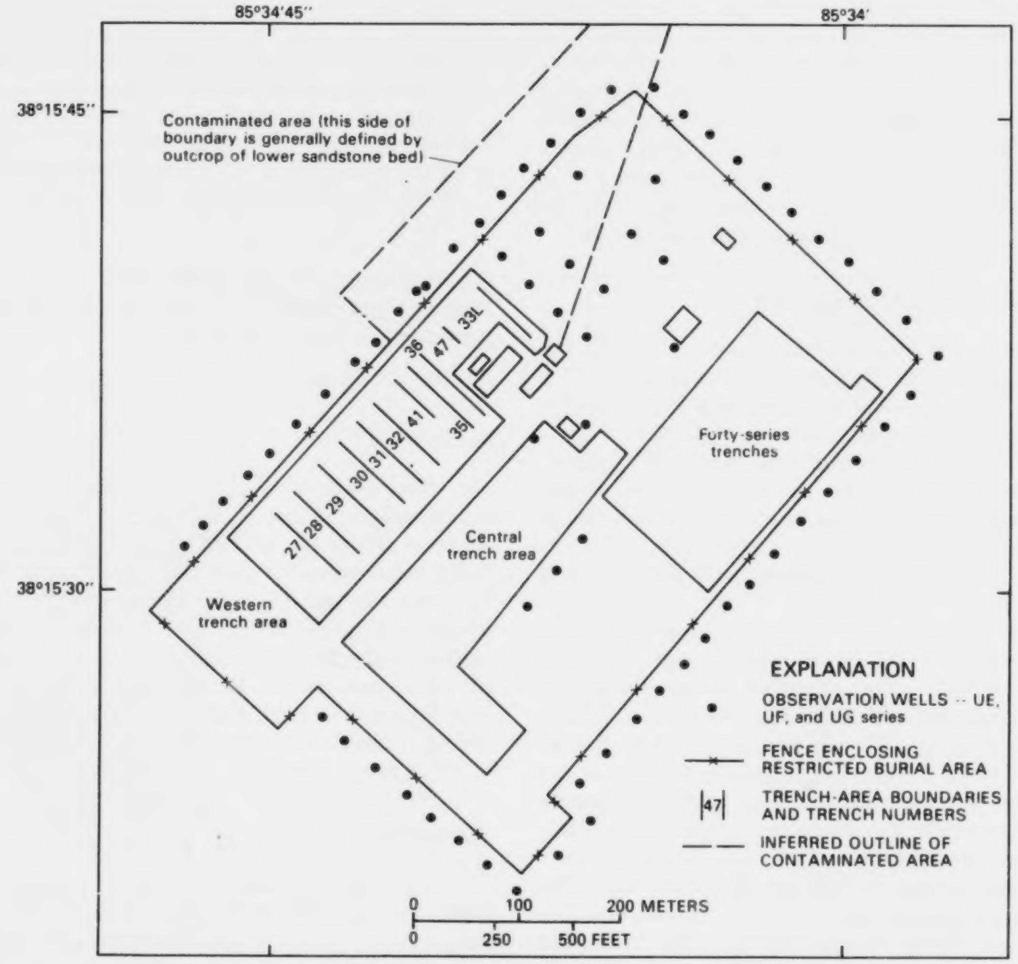
85°34'45"
85°34'
38°15'45"
38°15'30"
Contaminated area (this side of boundary is generally defined by outcrop of lower sandstone bed)
33L
47
36
41
32
31
30
29
28
27
35
Forty-series trenches
Central trench area
Western trench area
EXPLANATION
OBSERVATION WELLS -- UE, UF, and UG series
FENCE ENCLOSING RESTRICTED BURIAL AREA
TRENCH-AREA BOUNDARIES AND TRENCH NUMBERS
INFERRED OUTLINE OF CONTAMINATED AREA
0
100
200 METERS
0
250
500 FEET

Figure 19. Location of trenches, observation wells, and outline of contaminated area at the radioactive-waste repository site, Maxey Flats, Ky. Recent studies have verified that contaminated water has migrated from the burial grounds through the fractured lower sandstone bed of the Nancy Member.

decrease infiltration of precipitation into the closed burial trenches. One method selected to accomplish this objective was the emplacement of a 0.38- to 0.51-mm-thick PVC cover over the burial trenches. In order to determine the effectiveness of this cover, water-level data were collected in sumps from five trenches during May 1978 to October 1984; these dates spanned a period before and after the installation of the cover.

To analyze the effectiveness of the PVC cover, rainfall versus infiltration into the trenches were compared before and after the cover was in place. Within each trench, the water-level rise over the same interval of waste also was considered. For a more detailed discussion of PVC effectiveness, see Lyverse (1986).

Results of the analysis indicate that the PVC cover restricted water infiltration into the trenches. The ratio of infiltration to rainfall for the five trenches before emplacement of the PVC cover ranged from 5 to 37 percent. Infiltration after the PVC cover was emplaced indicated that 1.9 to 7.0 percent of rainfall reached the waste. In fact, most of the water reaching the waste after installation of the PVC cover probably is derived from lateral movement of ground water through the sides or bottom or both of the trenches and not by vertical movement through the PVC cover and cap. The PVC cover is replaced at intervals of about 1½ to 2 years (John Razor, Westinghouse Corporation, oral commun., 1988) because it decomposes by exposure to ultraviolet light.

Hillslope Processes at Maxey Flats

Accelerated erosional processes resulting from human-caused activities, such as emplacement of the PVC cover over the burial trenches, were the main impetus for a 3-year study of hillslope processes at the site.

Because of the almost impermeable PVC cover, runoff volumes and velocity have substantially increased in three main drainage channels. This increased runoff volume and velocity has caused accelerated bank enlargement in surrounding channels that drain water away from the site.

About 50 percent of the water drained from the PVC-covered area leaves the site through the main drainage channels. Channel-profile changes for several main drainage channel cross sections were compared with channel-profile changes from a drainage channel unaffected by the PVC cover. Comparisons indicate that the channel dimensions of the main drainage channels continued to adjust in order to reach equilibrium conditions several years after the PVC cover was put down.

Determinations of hillslope processes also were made using measurements of direct ground-surface lowering, measurements of sediment transport from small areas, and dendrochronologic techniques. Erosion pins and frames, as described by Goudie (1981), were used to record increments of ground-surface erosion. Gerlach troughs, consisting of an enclosed area that drains precipitation falling on the area into a trough and then into a sealed bottle, were used to measure sediment transport from small areas. Dendrochronology techniques, correlating tree rings with measured erosion near the tree bole, were used for comparison with erosion processes measured using the erosion frames and Gerlach troughs. The data from these sources is rather heterogeneous; efforts currently (1987) are underway to reduce the data to a form that is comparable to data obtained using other methods.

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Geohydrology of the Low-Level Radioactive-Waste Repository Site Near Barnwell, South Carolina

By Peter B. McMahon *and* Kevin F. Dennehy

Background

The low-level radioactive-waste repository site near Barnwell, S.C., is one of three active commercially operated sites in the United States. The site is operated by a private contractor on 121 ha of land leased from the State (figs. 20 and 21). Operation began in 1971 and is scheduled to continue until 1992. During 1986, about 45 percent of the Nation's low-level radioactive waste generated by non–Federal facilities was buried at the site near Barnwell. In total, 538,000 m^3 of low-level radioactive waste have been buried there since operations began in 1971 (Jump, 1986).

Geohydrologic Setting

The repository site is located in a humid coastal-plain. During 1983 and 1984, monthly precipitation ranged from 15 to 241 mm, monthly evapotranspiration ranged from 20 to 140 mm, and average daily air temperatures ranged from –9.2 to 31.9 °C (Dennehy and McMahon, 1987). Precipitation exceeded evapotranspiration during 14 of the 24 months, primarily in late fall, winter, and early spring; maximum excess precipitation, 115 mm, occurred in February of 1983. About 70 percent of the precipitation on the site was returned to the atmosphere by evapotranspiration.

The undisturbed unsaturated zone at the repository site consists of a few centimeters to about 1 m of surficial sand underlain by 10 to 15 m of clayey sand. Saturation ranges from about 20 to 100 percent in the surficial sand and 75 to 100 percent in the clayey sand.

The saturated zone above crystalline bedrock consists of about 320 m of generally unconsolidated clay, silt, sand and gravel, and limestone. The saturated deposits have been divided by Cahill (1982) into four water-yielding zones; the upper three zones are locally confined by discontinuous layers of clay and the lowest is continuously confined by about 15 m of dark lignitic clay. Flow in each water-yielding zone generally is to the south (Cahill, 1982). There also is a downward component of flow from the unsaturated zone to zones 1 (uppermost) through 4 (lowermost) (fig. 22). Hydrologic modeling of

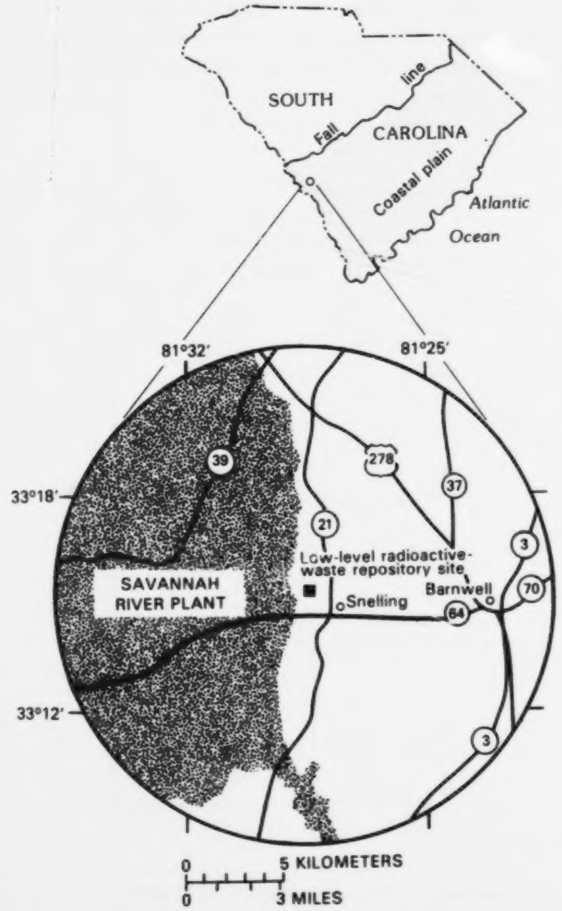
SOUTH
CAROLINA
Fall line
Coastal plain
Atlantic Ocean
81°32'
81°25'
33°18'
33°12'
39
278
37
21
3
70
64
3
Low-level radioactive-waste repository site
Barnwell
Snelling
SAVANNAH RIVER PLANT
0 5 KILOMETERS
0 3 MILES

Figure 20. Location of the low-level radioactive-waste repository site near Barnwell, S.C. The site is located on the humid coastal plain, east of the Savannah River Plant.

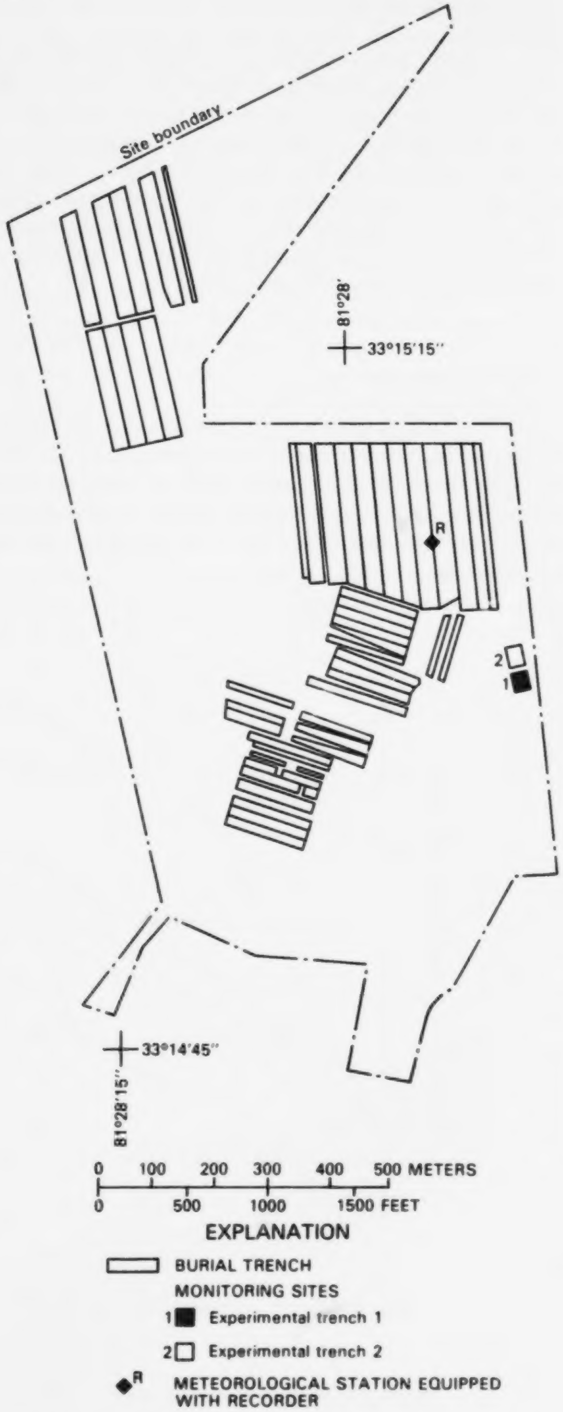
Site boundary
81°28'
33°15'15"
R
2
1
33°14'45"
81°28'15"
0 100 200 300 400 500 METERS
0 500 1000 1500 FEET
EXPLANATION
BURIAL TRENCH
MONITORING SITES
1 Experimental trench 1
2 Experimental trench 2
R METEOROLOGICAL STATION EQUIPPED WITH RECORDER

Figure 21. Location of burial trenches, monitoring sites, and meteorology station at the low-level radioactive-waste repository site near Barnwell, S.C.

the upper three zones by Cahill (1982) provided estimates of ground-water flow velocities in these zones. The average horizontal velocities in zones 1 through 3 were estimated at 1.2×10^{-2}, 7.6×10^{-2}, and 1.3×10^{-2} m/d, respectively.

Zones 1 and 2 receive recharge from the repository site and discharge into Marys Branch Creek about 1,000 m to the southwest. Zones 3 and 4 receive little, if any, recharge from the site; discharge from these zones is to streams farther from the site (Cahill, 1982). Thus, the majority of the precipitation at the site either returns to the atmosphere through evapotranspiration or reaches the water table and discharges to Marys Branch Creek through zones 1 and 2 (Cahill, 1982).

Trench Construction

Two trench designs have been used for most of the shallow-land burial at the repository site. Prior to 1976, trenches were about 152 m long, 15 m wide, and 7 m deep. Since 1976, trench dimensions have been increased to 305 m long and 30 m wide; the depth, 7 m, was unchanged.

The initial step during construction of the post-1976 trench is to excavate a 3-m-wide perimeter of surficial sand from around the designated trench area. Clayey sand is placed in the excavated area and compacted to construct an upper barrier wall. The compacted clayey sand prevents the upper wall from caving in and is a relatively impermeable surficial barrier compared to the surficial sand (U.S. Nuclear Regulatory Commission, 1982, p. 2–15). The trench is excavated within the clayey sand perimeter to a depth of about 7 m, but the depth may vary to maintain a minimum of 1.5 m between the trench bottom and water table. Trench floors are sloped to one side and along the long axis of the trench to promote drainage of water toward a French drain (fig. 23). Stand pipes and sumps used for monitoring are placed at regular intervals along the drain. Before the trench is filled with waste, sand is added to the trench floor to provide: (1) A firm and level base for the waste, (2) a porous medium for moisture to move to the French drain, and (3) a buffer zone in case of an abnormal rise in the water table (U.S. Nuclear Regulatory Commission, 1982, p. 2–17). After the waste packages have been emplaced and the trench has been backfilled with sand, a minimum of 0.6 m of clay is added to the top of the

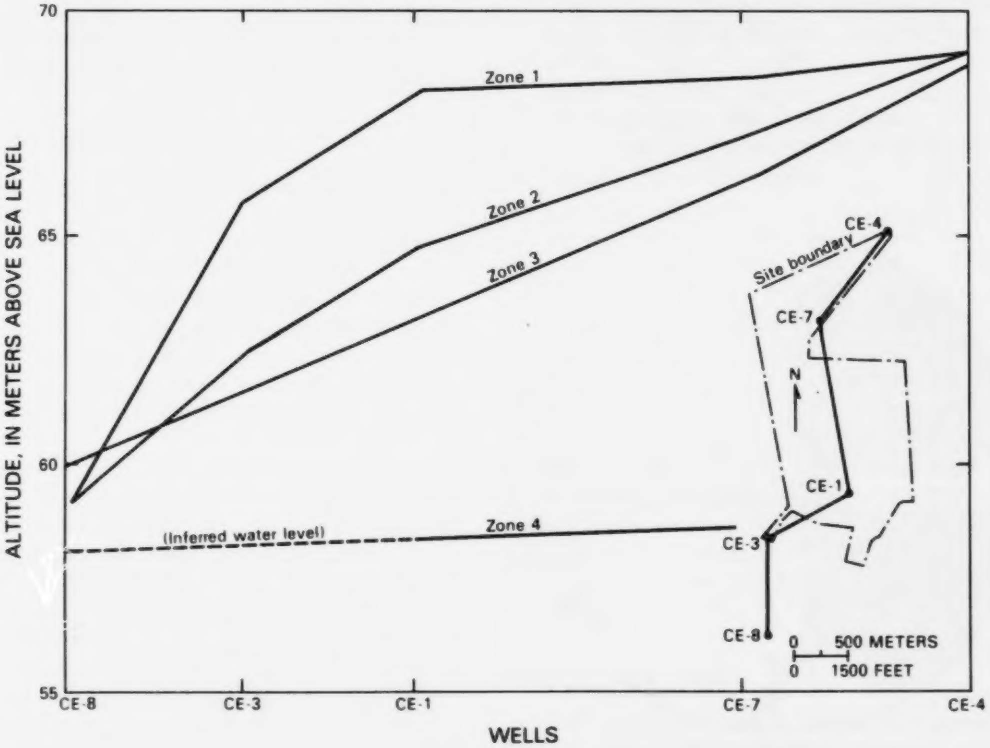

Figure 22. Altitude of potentiometric surface for four water-yielding zones during August 1977 at the low-level radioactive-waste repository site near Barnwell, S.C. (modified from Cahill, 1982). Sediments above zone 1 are unsaturated. There is a downward component of flow from the unsaturated zone to zones 1 through 4. Flow in each zone is generally to the south. Discharge from zones 1 and 2 is into Marys Branch Creek south of well CE–8.

trench and compacted with a vibrating compactor. At least 1 m of overburden is added over the clay. Lastly, the trench cover is contoured and sown with grass seed.

Pre-1976 trenches were constructed similarly, except they have shorter dimensions and no surficial barrier of compacted clayey sand around the trench perimeter.

Effect of Trench Design on Hydrology

Numerical simulations of water movement in the unsaturated zone at two experimental trenches (fig. 21), one constructed with the post-1976 design (experimental trench 1) and the other with the pre-1976 design (experimental trench 2), illustrate the effect of trench design on hydrology at the repository site. Modeling results for a period in 1984 indicate that water movement in the trench covers is affected by flux conditions on the land surface. During periods of evapotranspiration, water movement in the covers of both trenches was upward in the upper part of the cover but downward in the lower part of the cover (fig. 24). Water movement during storms was downward in both covers. The rate of unsaturated flow in the cover of experimental trench 1 was estimated at 3×10^{-6} cm/s (Dennehy and McMahon, 1987). In the undisturbed sediments adjacent to the trenches, water moved downward through the surficial sand and either continued downward into the undisturbed clayey sand or moved laterally along the contact between the surficial sand and the undisturbed clayey sand into the backfilled sand in the trench, depending on trench design. The use of the compacted clayey-sand barrier at experimental trench 1 greatly retarded water that moved along the contact from entering the trench; the absence of the barrier at experimental trench 2 allowed the water to enter the trench. The rate of unsaturated flow in the backfilled sand was estimated at 2×10^{-5} cm/s. Water ponded on the bottom of experimental trench 1 to a maximum depth of 0.3 m in 1984. At experimental trench 2, water ponded to a maximum depth of 2.3 m. About 0.41 m of excess precipitation was available for infiltration between June 1984 and July 1984; therefore, experimental trench 2 appeared to be a conduit for water recharging the saturated zone.

No ponded water was measured at monitoring sites in the post-1976 burial trenches. The nearly continuous minimal-permeability surface created by the compacted clayey-sand covers and barriers of adjacent trenches in the northern part of the site greatly increased surface runoff, thereby decreasing recharge throughout a large

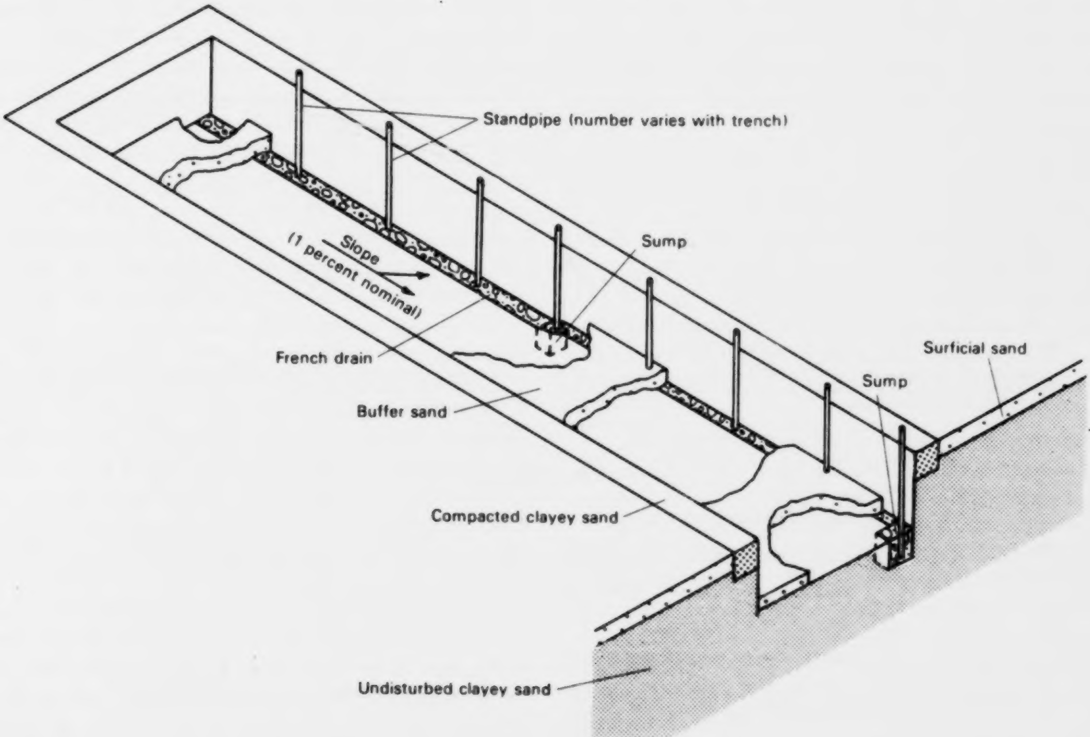

Figure 23. Typical post-1976 burial trench at the low-level radioactive-waste repository site near Barnwell, S.C. (modified from U.S. Nuclear Regulatory Commission, 1982). Sketch is not to scale.

part of the site. Long-term decreases in recharge may cause ground-water levels in this area to decline.

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Radioactive Gases at Low-Level Radioactive-Waste Repository Sites

By Robert G. Striegl

Land burial of low-level radioactive wastes can result in transport of radioactive gases through the surrounding unsaturated zone to ground water and the

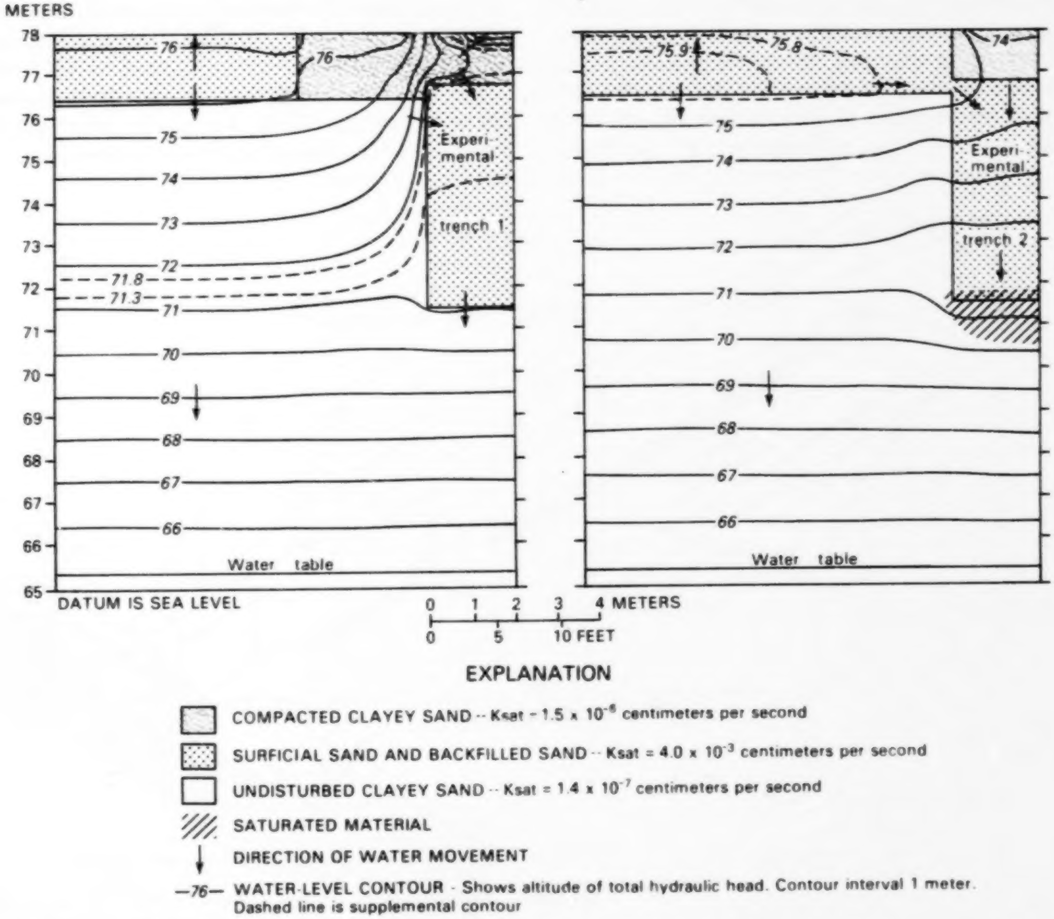
METERS
78
77
76
75
74
73
72
71
70
69
68
67
66
65
76
75
74
73
72
71.8
71.3
71
70
69
68
67
66
Experi-
mental
trench 1
Water table
DATUM IS SEA LEVEL
75.9
75.8
74
75
74
73
72
71
70
69
68
67
66
Experi-
mental
trench 2
Water table
0 1 2 3 4 METERS
0 5 10 FEET
EXPLANATION
COMPACTED CLAYEY SAND -- Ksat ~ 1.5 x 10-6 centimeters per second
SURFICIAL SAND AND BACKFILLED SAND -- Ksat = 4.0 x 10-3 centimeters per second
UNDISTURBED CLAYEY SAND -- Ksat = 1.4 x 10-7 centimeters per second
SATURATED MATERIAL
DIRECTION OF WATER MOVEMENT
—76— WATER-LEVEL CONTOUR - Shows altitude of total hydraulic head. Contour interval 1 meter. Dashed line is supplemental contour

Figure 24. Cross-sectional view showing simulated, total hydraulic-head distributions and flow directions at experimental trenches 1 and 2 on March 31, 1984, at the low-level radioactive-waste repository site near Barnwell, S.C. Water movement in the covers of both trenches was upward in the upper part of the cover but downward in the lower part of the cover during periods of evapotranspiration. During storms water movement was downward in both covers.

atmosphere, or in uptake of radionuclides by biological organisms. Sources for the gases include biological decomposition of wastes, chemical dissolution of wastes, volatilization of organic wastes, and radioactive decay of wastes. Radioactive gases identified at the low-level radioactive-waste repository near Sheffield, Ill., and near West Valley, N.Y., include $^{14}CO_2$; elemental ^{3}H; ^{3}H– water vapor; ^{14}C– and ^{3}H– methane, ethane, propane, and butane; ^{85}Kr; and ^{222}Rn (Lu and Matuszek, 1978; Husain and others, 1979; Striegl, 1984; 1988; Striegl and Ruhl, 1986). Additionally, several volatile organic compounds including alcohols, ketones, amines, aromatic hydrocarbons, ethers, and phenols have been identified in leachate from burial trenches that are likely to have gaseous-radioactive counterparts (Francis and others, 1980b). Of the identified sources for radioactive gases, biological decomposition of wastes seems to be the most significant.

The major end products of biological decomposition include CO_2, water vapor, and methane. Laboratory investigations have demonstrated that soil and leachate micro-organisms can produce ^{3}H– water vapor and methane, and $^{14}CO_2$ and ^{14}C– methane from substrates containing those radioisotopes (McFarlane and others, 1978; Francis and others, 1980a). Production of biogenic gases is limited by availability of substrate, moisture, and temperature. The radioisotope concentration of the gases produced is determined by the specific radioactivity of the decomposing waste, and varies greatly within and between burial trenches. Because large void spaces occur between buried waste containers and are created as waste consolidates and decomposes, it is thought that gases are well mixed within burial trenches. Subsequent movement of the gases away from the burial trenches may be dominated either by diffusion or by coupled advection plus diffusion, depending on the rate and volume of gas production and on local boundary conditions.

Where partial pressures of gases produced are small relative to total barometric pressure, it generally is assumed that total gas pressures are equal at any given altitude and that transport of trace quantities of waste-produced gases is controlled by ordinary diffusion along partial-pressure gradients. This situation conceivably occurs where the water contents of the decomposing waste and of the burial-trench materials are small enough, and their air-filled porosities are great enough, to allow sufficient pneumatic connection so that partial pressures of major gases in the burial trenches are similar to those in the surrounding geologic materials. Molecular diffusion of the trace gases through the surrounding unsaturated zone is affected by pore-size distributions, air- and water-filled pores, and by chemical and physical interactions that occur between gases, water, and solids (Millington, 1959; Evans, 1965; Lai and others, 1976; Weeks and others, 1982; and Thorstenson and others (1983).

The low-level radioactive-waste repository site near Sheffield, Ill. (fig. 1), has similar characteristics to those described above and was the location for intensive studies (fig. 25) that identified the spatial and temporal distributions of gases in the unsaturated zone near buried wastes (Striegl, 1984; 1988; Healy and others, 1986; Striegl and Ruhl, 1986). These studies verified that $^{14}CO_2$ and methane were produced by the decomposition of waste and diffused through the surrounding unsaturated zone, whereas partial pressures of $^{14}CO_2$ and other major atmospheric gases remained similar between test wells at similar altitudes.

Time-averaged mean partial pressures of $^{14}CO_2$ were more than 640,000 times greater than the atmospheric partial pressure at piezometer A2, located 12 m from burial-trench 2 and 12 m below the land surface (fig. 26). Partial pressures decreased with distance from the burial trench and with proximity to the land surface (table 4). Current (1987) $^{14}CO_2$ research is focused on isolating and quantifying processes that control the diffusion of the $^{14}CO_2$ in the unsaturated zone. Dominant processes include involvement of $^{14}CO_2$ in carbonate-equilibrium reactions (Thorstenson and others, 1983) and carbon-isotope exchange between gaseous, aqueous, and solid inorganic-carbon reservoirs. The magnitude of the gaseous-carbon reservoir was determined by measurement of CO_2 partial pressures, the aqueous inorganic-carbon reservoir was estimated using thermodynamic constants for CO_2-water-calcite equilibria, and the reservoir for CO_2 associated with solids was estimated from experimentally determined CO_2-sorption isotherms.

Partial pressures of methane also were greatest at piezometer A2 and decreased with distance from burial trench 2 (table 5). Methane partial pressures were less than atmospheric near the land surface, indicating consumption of both waste-produced and atmospheric methane by soil micro-organisms. Current (1987) methane research is focused on quantifying the physical impedance to diffusion (Striegl and Ishii, 1987) and the biological consumption of methane in the unsaturated zone.

No greater than background partial pressures of ^{3}H– water vapor were detected within the gas-sampling network at the repository site. This is apparently because ^{3}H in water vapor exchanges with hydrogen in pore water at locations much nearer burial trench 2 than the closest soil-gas piezometer. The molar gradient of liquid water to water vapor per unit volume of the unsaturated zone is about 20,000 to 1. Tritium also can exchange between liquid water, water vapor, and a variety of hydrogen-containing functional groups on organic molecules (Francis and others, 1980a).

Ethane, propane, and butane routinely were analyzed for in gas samples collected from the sampling network, but no partial-pressure gradients were detected at a detection limit of 0.5 ppm. Prior to initiation of the unsaturated-zone study, analyses of six 145–L samples that were collected from a soil-gas piezometer located in a tunnel beneath the buried waste indicated that, although ^{14}C activity in CO_2 was about equal to the total ^{14}C activity in the samples, some ^{14}C was present in the trace quantities of methane, ethane, propane, and butane present in the samples. Analyses of two 410–L samples collected from the same location indicated that ^{3}H activ-

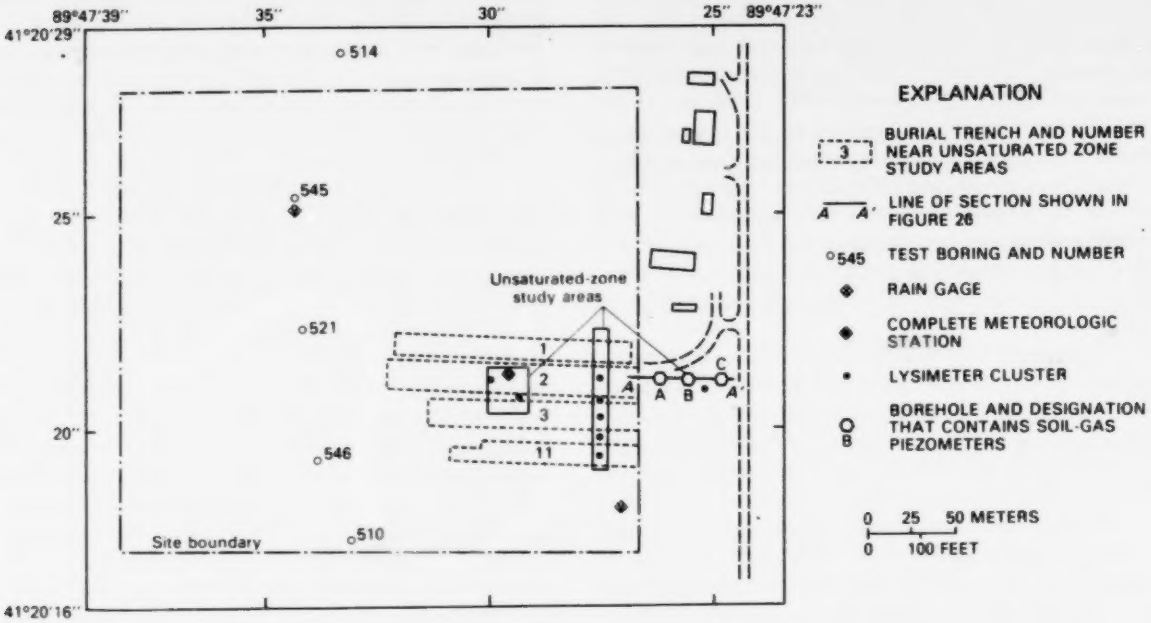
89°47'39"
35"
30"
25"
89°47'23"
41°20'29"
25"
20"
41°20'16"
514
545
521
546
510
Site boundary
Unsaturated-zone study areas
1
2
3
11
A
B
C
A'
EXPLANATION
3 BURIAL TRENCH AND NUMBER NEAR UNSATURATED ZONE STUDY AREAS
A A' LINE OF SECTION SHOWN IN FIGURE 26
545 TEST BORING AND NUMBER
RAIN GAGE
COMPLETE METEOROLOGIC STATION
LYSIMETER CLUSTER
B BOREHOLE AND DESIGNATION THAT CONTAINS SOIL-GAS PIEZOMETERS
0 25 50 METERS
0 100 FEET

Figure 25. Low-level radioactive-waste repository site near Sheffield, Ill., showing location of unsaturated-zone study areas, burial trenches, and data-collection instruments. Long dashes on right represent unnamed road; rectangles left of road represent buildings.

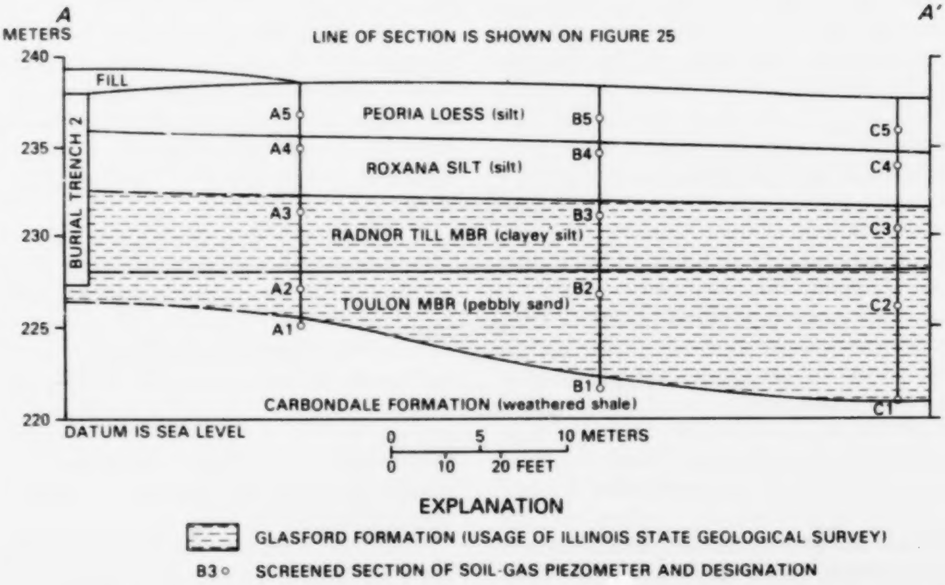
A
A'
METERS
LINE OF SECTION IS SHOWN ON FIGURE 25
240
235
230
225
220
FILL
BURIAL TRENCH 2
PEORIA LOESS (silt)
ROXANA SILT (silt)
RADNOR TILL MBR (clayey silt)
TOULON MBR (pebbly sand)
CARBONDALE FORMATION (weathered shale)
A5
A4
A3
A2
A1
B5
B4
B3
B2
B1
C5
C4
C3
C2
C1
DATUM IS SEA LEVEL
0 5 10 METERS
0 10 20 FEET
EXPLANATION
GLASFORD FORMATION (USAGE OF ILLINOIS STATE GEOLOGICAL SURVEY)
B3 SCREENED SECTION OF SOIL-GAS PIEZOMETER AND DESIGNATION

Figure 26. Lithology and location of soil-gas piezometers at the low-level radioactive-waste repository site near Sheffield, Ill.

Table 4. Time-weighted mean partial pressure of carbon-14 dioxide in the unsaturated-zone atmosphere at the low-level radioactive-waste repository site near Sheffield, Ill.

Depth of screened interval below land surface (meters)	Borehole A		Borehole B		Borehole C	
	Designation of screened interval of soil-gas piezometer	Time-weighted mean partial pressure of 14-carbon dioxide (pascals)	Designation of screened interval of soil-gas piezometer	Time-weighted mean partial pressure of 14-carbon dioxide (pascals)	Designation of screened interval of soil-gas piezometer	Time-weighted mean partial pressure of 14-carbon dioxide (pascals)
0	Atmosphere	3.96×10^{-11}	Atmosphere	3.96×10^{-11}	Atmosphere	3.96×10^{-11}
3.7	A4	5.80×10^{-6}	B4	3.54×10^{-7}	C4	5.90×10^{-9}
7.3	A3	1.19×10^{-5}	B3	3.89×10^{-6}	C3	7.45×10^{-7}
11.6	A2	2.54×10^{-5}	B2	7.88×10^{-6}	C2	7.48×10^{-7}
13.6	A1	2.03×10^{-5}				

Table 5. Time-weighted mean partial pressure of methane in the unsaturated-zone atmosphere at the low-level radioactive-waste repository site near Sheffield, Ill.

Depth of screened interval below land surface (meters)	Borehole A		Borehole B		Borehole C	
	Designation of screened interval of soil-gas piezometer	Time-weighted mean partial pressure of 14-carbon dioxide (pascals)	Designation of screened interval of soil-gas piezometer	Time-weighted mean partial pressure of 14-carbon dioxide (pascals)	Designation of screened interval of soil-gas piezometer	Time-weighted mean partial pressure of 14-carbon dioxide (pascals)
0	Atmosphere	0.17	Atmosphere	0.17	Atmosphere	0.17
1.8	A5	.08	B5	.07	C5	.08
3.7	A4	.17	B4	.08	C4	.09
7.3	A3	.4.7	B3	.68	C3	.35
11.6	A2	1.54	B2	.76	C2	.39
13.6	A1	1.56				

ity in organic gases exceeded ^3H activity in water vapor by a factor of about 30 and that ^3H activity increased in heavier gases. The reverse trend was determined for organic gases collected at the low-level radioactive-waste repository site near West Valley, N.Y. (C.O. Kunz, New York State Department of Health, written commun.,1983). Although no further research has been conducted to define radionuclide transport in organic gases near buried low-level waste, it is a topic that needs to be addressed.

Where production of biogenic gases is sufficiently large to measurably increase the total gas pressure, gas transport is controlled by coupled advection plus diffusion (Alzaydi and others, 1978). Although not specifically documented for low-level radioactive-waste repository sites, substantial production of CO_2 (Enoch and Dasberg, 1971; Norstadt and Porter, 1984) or methane (McOmber and others, 1982) may locally displace other atmospheric gases from the unsaturated zone. At repository sites where this occurs, wastes typically would be buried in areas that have high water contents or that are covered by tightly compacted layers which impede circulation of gases between the waste and the atmosphere.

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Leachate Geochemistry at Low-Level Radioactive-Waste Repository Sites—Effects of Site Geohydrology on Nature and Production of Leachates

By Mark Fuhrmann *and* Peter Colombo

The effect of low-level radioactive waste on water moving into shallow burial trenches is in part a function of the residence time of the water as it contacts the buried waste. Other factors that affect water chemistry are: (1) The total water available, (2) the mobility of various components of the waste, and (3) the physical form and packaging condition of the waste. An extensive sample-analysis program at the Brookhaven National Laboratory sponsored by the U.S. Nuclear Regulatory Commission has characterized the chemistry of leachates from burial trenches at four low-level radioactive-waste repository sites. Selected analytical data for samples of leachate from eight burial trenches at three of these repository sites are listed in table 6. These and other analytical data indicate that the waste dominates water chemistry in the burial trenches, typically resulting in larger concentrations, in comparison with local well water, of total alkalinity, dissolved organic and inorganic carbon, chloride, ammonia, sodium, potassium, dissolved iron and manganese, as well as radionuclides, particularly ^{137}Cs, ^{60}Co, and ^{3}H (Weiss and Colombo, 1980; Czyscinski and Weiss, 1981; Dayal and others, 1986b).

Leachates from burial trenches generally are anoxic as a result of biodegradation of organic waste. Values of Eh typically are about +150 mV (NHE), but values as small as -56 mV (NHE) have been measured (Czyscinski and Weiss, 1981). Sulfate concentrations commonly are small compared to local well water, indicating bacterial use of sulfate as an oxidant. At typical values of Eh, iron and manganese are reduced and in solution. Anoxic biodegradation also causes increased alkalinity and ammonia concentrations.

Water in burial trenches, particularly from older repository sites, contains a myriad of organic compounds (Czyscinski and Weiss, 1981). Some of these, such as EDTA, are complexed with radionuclides (particularly cobalt and transuranic elements) and lead. This complexing enhances mobility from burial trenches and waste forms in lysimeter experiments (Means and others, 1978; Cleveland and Rees, 1981; Walter and others, 1986).

Changes in ground-water chemistry induced by waste disposal are temporary. As the waste decomposes, causing conditions in the burial trench to become reducing, nutrients are used by bacteria and eventually conditions in the burial trench become more oxidized. In addition to biological action, the use of cement as a solidification agent and in engineered repository structures affects the chemistry of the water in burial trenches.

To investigate how changes in Eh and alkalinity can affect contaminant concentrations in burial-trench leachates, samples of anoxic leachate from several burial trenches at the Maxey Flats low-level radioactive-waste repository site in Kentucky were exposed to air. Oxides of iron precipitated and were filtered from the supernate. Some changes in leachate chemistry after oxidation, as compared to anoxic leachate, are listed in table 7. Increases in Eh were accompanied by increases in pH. Almost all the iron was precipitated, but only small

Table 6. Selected analytical data for burial-trench leachates from three low-level radioactive-waste repository sites

[Data from Dayal and others (1986b). Eh, oxidation-reduction potential; mV, millivolts; NHE, normal hydrogen electrode; µS/cm, microsiemens per centimeter at 25 degrees Celsius; mg/L, milligrams per liter; nCi/L, nanocuries per liter]

Repository site and burial-trench number	Eh (mV, NHE)	Specific conductance (µS/cm)	Iron (mg/L)	Magnesium (mg/L)	Cesium-137 (nCi/L)	Cobalt-60 (nCi/L)	Strontium-90 (nCi/L)	Tritium (nCi/L)
Maxey Flats, Ky.								
7	–44	12,000	17	193	36	17	11,000	30,000
19s	–28	2,100	65	128	6.1	6.9	2,400	70,000
17	17	6,000	1,250	350	9.3	5.3	140	2,300,000
35	–14	3,400	1	330	5.2	0.2	15	3,700,000
West Valley, N.Y.								
3	–3	7,600	56	180	1,200	23	840	350,000
9	18	3,400	57	150	30	0.7	200	350,000
Near Barnwell, S.C.								
6	350	260	< 1	1	--	< 0.002	< 0.0004	620
8	130	2,600	24	40	--	0.003	< 0.004	390,000

Table 7. Chemical changes induced by oxidation of burial-trench leachates from the low-level radioactive-waste repository site, Maxey Flats, Ky.

[Eh, oxidation-reduction potential; mV, millivolt]

Burial-trench number	Eh (mV) change	pH change	Iron	Magnesium	Total solids	Cesium-137	Cobalt-60	Strontium-85
Trench 7	+410	+1.8	100	24	23	6.2	36	15.1
Trench 19s	+320	+0.9	99	1.0	24	0	0	19.0
Trench 26	+270	+0.4	97	2.0	6.3	0	0	16.2
Trench 27	+370	+0.8	100	3.4	8.8	0	9.5	14.1
Trench 32	+340	+1.8	95	11	4.4	0	2.6	12.5

quantities of magnesium were precipitated. Precipitation of radionuclides was inconsistent. In leachate from burial trench 7, 36 percent of the ^{60}Co was precipitated by oxidation, but, in most cases, little, if any, ^{137}Cs or ^{60}Co was precipitated. Between 12.5 and 19.0 percent of ^{85}Sr (which was added to anoxic leachates to simulate ^{90}Sr) was precipitated. Iron oxyhydroxides have been reported to have substantial capacity to adsorb metals (Jenne, 1968) and oxidation of trench leachates does precipitate iron oxyhydroxides; but in this case, these minerals have little capacity to sorb radionuclides from actual burial-trench leachates.

It also is possible to precipitate contaminants by increasing the pH of burial-trench leachates. Some results of increasing the solution pH by adding varying quantities of sodium hydroxide to oxidized leachates from two burial trenches at the Maxey Flats site are listed in table 8. All iron was precipitated by small additional quantities of sodium hydroxide, whereas increasing percentages of magnesium precipitated as the sodium hydroxide concentration increased. Most of the ^{60}Co was precipitated when the pH was increased to about 13, but there was little change in leachate concentrations of ^{137}Cs. Strontium-85 also precipitated as the pH was increased; maximum precipitation occurred at pH 12.4. Further increases in pH resulted in decreased ^{85}Sr precipitation. This response is shown in figure 27 for reduced and oxidized burial-trench leachates.

This information indicates the chemistry of leachate changes that may be expected in a burial-trench environment consisting of radioactive waste, ground water, and an engineered barrier constructed of cement depends on alkaline conditions.

In existing and future repository sites, it is unlikely that the extreme hydrologic conditions that result in constantly saturated conditions in burial trenches will be

Table 8. Chemical changes induced by oxidation and pH adjustment of burial-trench leachates from the low-level radioactive-waste repository site, Maxey Flats, Ky.

[µmol/mL, micromoles per milliliter]

Burial-trench number	Sodium hydroxide added (µmol/mL)	pH change	Iron	Magnesium	Total solids	Cesium-137	Cobalt-60	Strontium-85
Trench 7	10	[1]+1.9	100	31	26	7	60	0
	20	+4.3	100	66	30	7	71	29
	40	+5.2	100	98	39	9	83	76
	80	+5.6	100	100	42	10	85	75
Trench 27	5	[2]+1.7	100	14	6.7	0	0	17
	15	+3.1	100	21	12	0	0	27
	30	+3.8	100	86	25	0	29	74
	50	+4.9	100	100	26	0	92	89
	100	+5.2	100	100	24	0	94	77

[1] Original pH was 7.4.

[1] Original pH was 7.5.

allowed to develop. In addition, much of the waste is now (1987) solidified or suitably contained to decrease leaching and improve trench stability. Wastes with large concentrations of complexing agents are segregated as outlined by the U.S. Nuclear Regulatory Commission (1983).

The hydrologic conditions at newer repository sites combined with improvements in waste forms will result in different conditions of leachate production than the constant saturation at older sites. Leachate production at newer repository sites will be affected by the alkalinity of cement waste forms and by intermittent periods of leaching by ground water, followed by periods of drying, or at least less soil moisture.

Leaching studies at the Brookhaven National Laboratory (sponsored by the Nuclear Regulatory Commission) were conducted where cement waste forms containing an ion-exchange resin were exposed to alternating wet/dry cycles of various durations (Dayal and others, 1983; Dayal and others, 1986a). As expected, the

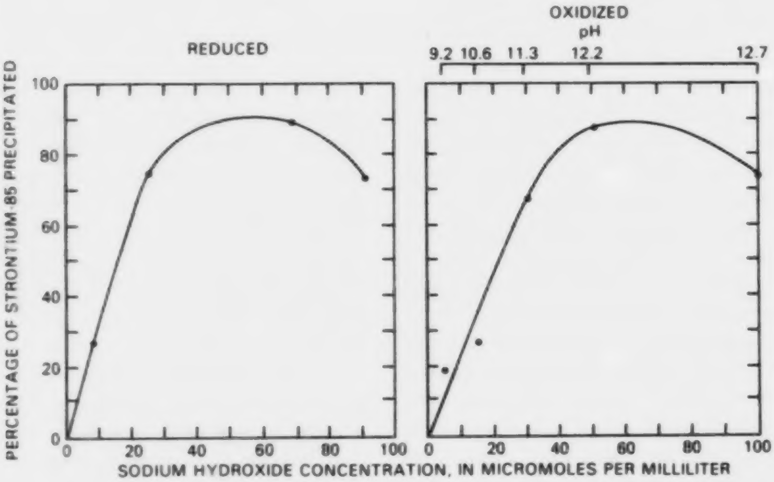

Figure 27. Percentage of strontium-85 precipitated by various sodium hydroxide concentrations for reduced and oxidized burial-trench leachates from burial trench 27, low-level radioactive-waste repository site, Maxey Flats, Ky. Black dots represent sampling points.

leach rate for ^{137}Cs was slower for wet/dry-cycled specimens than the rate for constantly saturated specimens when overall test duration was considered. However, if the data were analyzed considering the total time under saturated conditions, the leach rate for ^{137}Cs was somewhat faster for wet/dry-cycled specimens than for constantly saturated specimens. A trend was determined that indicated faster leaching rates for ^{137}Cs with increased duration of drying periods. This was explained by replenishment, during drying, of ^{137}Cs to the leaching surface from the less depleted interior of the specimen—an efflorescence process. When water again was introduced to the system during the wet cycle, enhanced leaching occurred because of large Cs-137 concentrations at the waste-form surface. Leaching of ^{85}Sr was determined to be substantially decreased after drying. This was attributed to increased curing of the cement during drying.

More recent work at Brookhaven National Laboratory pertaining to development of an accelerated leach test (Dougherty and others, 1986; Fuhrmann and Colombo, 1989) for the U.S. Department of Energy's National Low-Level Waste Program has resulted in the determination and interpretation of elemental profiles that develop inside waste forms as a result of leaching. This effort has illustrated how the efflorescence process occurs and how complicated leaching transport can be in the repository-site environment.

Portland type I cement specimens were produced using a water-to-cement ratio of 0.43; these specimens have an estimated porosity of about 58 percent. Identical specimens were leached at 20 °C for about 500 days and at 30 °C for 18 days to obtain two different states of depletion of the soluble cement components. Leaching of Cs has been determined to be a temperature-activated process that is mechanistically unaltered at temperatures as high as 50 °C (Fuhrmann and others, 1987). It also has been determined that potassium originating in the cement leaches identically to ^{137}Cs tracers (Fuhrmann and Colombo, 1989).

A profile of the potassium to magnesium ratio determined by energy-dispersive spectroscopy in the cement specimen leached for about 500 days is shown in figure 28. This ratio was used so that magnesium could be used as an internal reference. The original potassium to magnesium ratio of the unleached cement is shown as the line near the center of the figure. With the exception of one analysis, no potassium was detected to a depth of 9 mm from the surface of the specimen. From 9 mm to the center of the specimen, the ratio increased in what appears to be a linear manner. This profile illustrates leaching of an element that has little reaction with the cement and is governed primarily by a diffusion process.

In contrast, the potassium to magnesium ratio for a specimen that was leached and then air dried at 29 °C prior to sectioning is shown in figure 29. Potassium increased from the surface of the specimen to a maximum ratio (almost double the original ratio of the unleached sample) at a depth of 7.5 mm. From a depth of 11 to 15 mm, no potassium was detected; from a depth of 15 mm to the center, the potassium increased again. The surface of the specimen was coated with calcium carbonate, which effectively decreased any porosity visible by scanning-electron microscopy.

The potassium to magnesium profile of the dried specimen is analogous to one that would form under

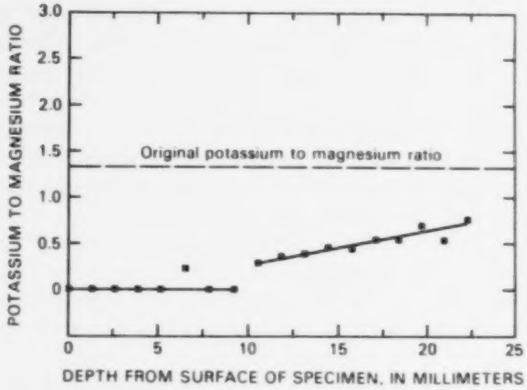

Figure 28. Internal profile of the potassium to magnesium ratio in a leached cement specimen; profile is attributed to a single process. This profile illustrates leaching of an element that has little reaction with the cement and is governed primarily by a diffusion process. Black squares represent potassium to magnesium ratio measured at indicated depth from surface in a leached cement specimen.

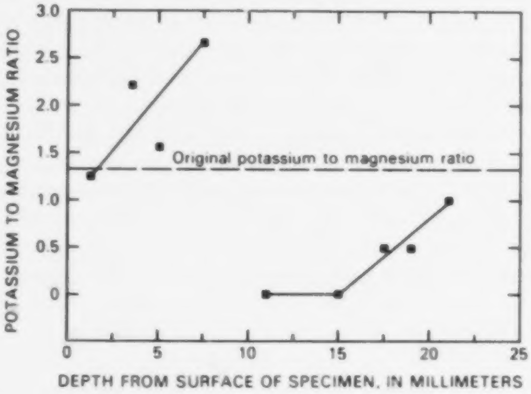

Figure 29. Internal profile of the potassium to magnesium ratio in a leached cement specimen after drying; profile is attributed to several processes. This profile is analogous to one that would form under wet/dry cycling conditions. Black squares represent potassium to magnesium ratio measured at indicated depths from surface in a leached cement specimen after drying.

wet/dry cycling conditions. This profile may be explained by three processes that affected leaching. During the wet part of the cycle, leaching proceeded primarily by diffusion through a porous medium. With drying, capillary action caused pore water containing dissolved species to move to the surface of the specimen. Simultaneously, a rapidly precipitating coating of calcium carbonate formed on the surface and in the near-surface pores of the specimen as it was exposed to air. The profile that resulted indicated no potassium at the surface and maximum accumulation of potassium at a depth of 7.5 mm. At depths from 11 to 15 mm, there was a depleted zone where the potassium had been leached and drawn toward the surface of the specimen. Closer to the center of the specimen the profile resembled that of the primary diffusive leaching process. Therefore, three processes that affect mass transport from the waste form have been determined: (1) Diffusive leaching, (2) evaporative transport of pore water by capillary action, and (3) reactions with air (or soil gases) causing alteration of the waste-form surface and changes in porosity. This latter process also explains the rapid decrease in the leach rate of ^{85}Sr that occurs during drying. Strontium-85 was immobilized by the calcium carbonate, which probably incorporated strontium as a solid solution (Pingitore and Eastman, 1986).

An experiment was made to clarify the process that caused concentration of potassium in a zone inside the leached and dried specimen. Six samples, three from the surface and three from the center of the leached cement specimen, were used in the experiment. The powdered samples, which weighed 0.25 g each, were put into 20 mL of distilled water containing 6,000 Bq of ^{137}Cs. After 10 days aliquots were removed, filtered, and analyzed for ^{137}Cs. Distribution coefficients of ^{137}Cs were determined to be 2,400 for the surficial calcium carbonate layer, but they were 11 for the cement from the center of the same specimen. This large distribution coefficient for the surface material explains the accumulated potassium at a depth of 7.5 mm inside the solid specimen.

Additional experiments are underway at Brookhaven National Laboratory to determine the leaching characteristics of waste forms in anoxic waters containing large quantities of ferrous iron and complexing agents in order to better understand how leachates are produced in actual repository-site environments.

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Mixed-Waste Leachates in Ground Water at Low-Level Radioactive-Waste Repository Sites

By Daniel J. Goode

Background

It has been recognized for some time that low-level radioactive waste may contain nonradiological hazardous constituents (General Research Corp., 1980). Such waste commonly is referred to as "mixed waste." Bowerman and others (1985) surveyed operators of facilities generating low-level radioactive waste and identified three waste types that should be tested to determine if they constitute hazardous waste. These waste types are organic liquid wastes, lead-shielding and lead-container wastes, and light-water-reactor process wastes containing chromium. The organic liquid wastes reported in the survey were scintillation liquids and vials (73 percent by volume), laboratory liquids (18 percent), and miscellaneous solvents (9 percent). Toluene and xylene are the primary organic-chemical components in scintillation vials.

On the basis of their predominance in low-level radioactive waste, it would be expected that toluene and xylene would be the most likely organic chemicals to be detected at concentrations greater than background concentrations if organic chemicals are migrating from burial trenches at low-level radioactive-waste repository sites. Likewise, lead and chromium would be the hazardous metals most likely to be present in ground water in the vicinity of the burial trenches. These hypotheses, however, do not consider other factors that affect the migration, persistence, and fate of solutes in ground water, including biodegradation, sorption, and volatilization. All of these processes are controlled by site-specific geochemical conditions that may vary in time and space.

Personnel from the U.S. Nuclear Regulatory Commission and the Oak Ridge National Laboratory, Tennessee, sampled ground-water wells at the low-level radioactive-waste repository sites near Sheffield, Ill., and near Barnwell, S.C. In addition, available information from these and other commercially operated low-level radioactive-waste repository sites were reviewed to assess the occurrence of mixed-waste leachates in ground water at these sites.

Repository Site Near Sheffield, Illinois

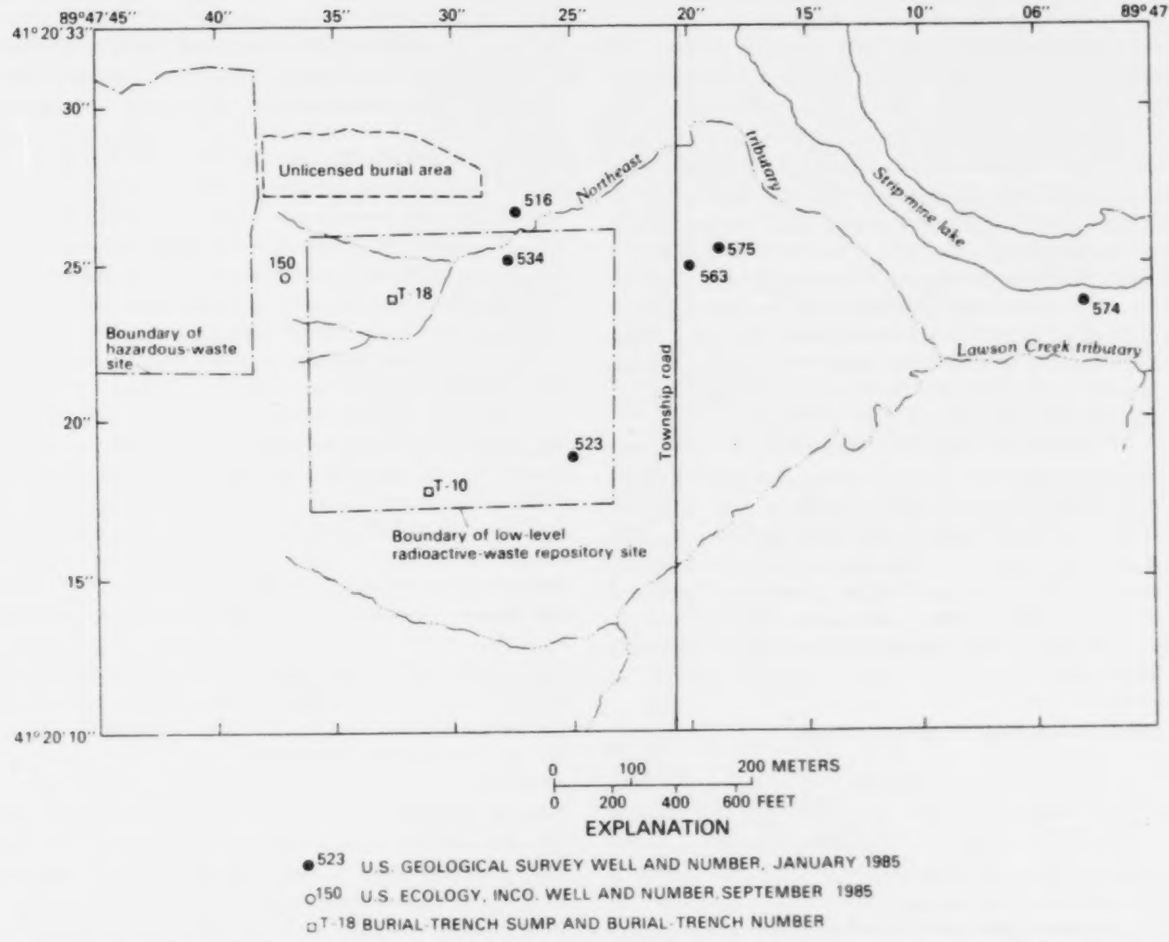
Waste buried near Sheffield, Ill. (fig. 1), included materials containing organic chemicals such as "tritiated oil" and "labeled organics" (McKenzie and others, 1985). Tritium is migrating from the burial trenches in ground water and has resulted in concentrations of about 50 nCi/L in water from nearby offsite wells (Foster and others, 1984b). These concentrations were detected in the northeast corner of the site where a narrow, shallow depression in the almost impermeable till unit underlying the site is filled by a pebbly sand unit (Foster and others, 1984a). Results of a natural-gradient tracer test in the pebbly sand unit indicate that the ground-water velocity is about 2 m/d (Garklavs and Toler, 1985). Most of the ground-water discharge from the site occurs through the pebbly sand unit (Garklavs and Healy, 1986). Site features and location of wells and trench sampled for organic and other nonradiological hazardous constituents are shown in figure 30.

Personnel from the Brookhaven National Laboratory, the U.S. Geological Survey, the Illinois Department of Nuclear Safety, and the Illinois Environmental Protection Agency had previously sampled and analyzed ground water for organic constituents. These analyses indicated several organic constituents in ground water in and near the repository site. However, almost all the wells sampled are located so that they could be affected by disposal of chemical waste either at the adjacent hazardous-waste site operated by the Illinois Environmental Protection Agency or at the unlicensed burial ground north of the low-level radioactive-waste repository site (fig. 30). Organic constituents detected included trichloroethylene, trichloroethane, tetrachloroethylene, dichloroethane, and chloroform. The maximum concentration of tetrachloroethylene, 0.12 mg/L, was measured in water from well 563. Weiss and Colombo (1980) reported "organic carbon" concentrations of 50 mg/L in water from the sump at burial trench 10 and 40 mg/L in water from well 523. The facility operator, U.S. Ecology, Inc., also analyzed ground water for a few organic constituents and reported that no toluene or xylene was measured at concentrations exceeding the detection limit of 0.01 mg/L in water from nine onsite and offsite wells (W.K. Waller, U.S. Ecology, Inc., written commun., 1984).

In January 1985, water samples were collected by the author from four wells and from the sump of burial-trench 18. On September 18, 1985, water samples were collected from seven wells by Oak Ridge National Laboratory staff, with the assistance of U.S. Ecology personnel. Details of the sampling and analysis procedures and results are reported by Ketelle and others (1986). Concentrations of volatile organic compounds are listed in table 9.

In general, burial trench 18, sampled on the repository site, and wells completed in the pebbly sand unit off the site contained water with large concentrations of several constituents. Concentrations of magnesium, bicarbonate, sulfate, manganese, and total organic carbon were all larger in water from burial trench 18 and wells 523, 563, and 575 than in water from wells 150, 516, 534, and 574, considered to represent background. Concentrations of organic compounds also were large in water from several wells. Water from wells 523, 563, and 575 contained 1,1,1-trichloroethane in estimated concentrations of 12, 3.2, and 2.5 mg/L, respectively. The tetrachloroethylene concentration in water from well 516 was estimated to be 1.4 mg/L. Large concentrations of benzene, 1,1-dichloroethane, and chloroform were detected. Trichloroethylene was detected in water from four wells; the maximum concentration was 0.022 mg/L in water from well 516. The sample from well 574, the background well, contained 0.006 mg/L 1,1,1-trichloroethane and 0.001 mg/L methylene chloride. Five volatile organic compounds were identified in water from well 150 at concentrations less than 0.006 mg/L. Five volatile organic compounds were present at less than the detection limits (0.001 mg/L) in water from well 534. Toluene was present at less than the detection limit (0.001 mg/L) in water from wells 516, 523, 534, and 575. Xylene was not detected in any sample. Hydrocarbons associated with petroleum products were detected in all wells sampled (Ketelle, 1986).

Organic-chemical concentrations are positively correlated with ^{3}H concentrations at the repository site. Concentrations of total organic carbon and 1,1,1-trichloroethane increase with increasing ^{3}H concentrations for the wells sampled (figs. 31 and 32). The ^{3}H concentrations measured in the present sampling effort are consistent with previous data (Foster and others, 1984b) (indicating that the organic-constituent concentrations also should be fairly representative of existing ground-water conditions). The correlation between ^{3}H and organic-chemical concentrations supports the hypothesis that at least some of the organic chemicals are associated with the ^{3}H source, specifically the low-level radioactive-waste burial trenches. It appears that organic chemicals are migrating from the low-level radioactive-waste burial trenches along with ^{3}H. Where ^{3}H is not correlated with the organic-chemical concentration, tetrachloroethylene at well 516 for example, the organic chemicals primarily are from some source other than the low-level radioactive-waste burial trenches (fig. 33). The correlation between ^{3}H and organic chemicals from the low-level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40"
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41°20'33"
30"
25"
20"
15"
41°20'10"
Unlicensed burial area
516
Northeast
tributary
Strip-mine lake
150
534
575
563
T-18
574
Boundary of hazardous-waste site
Lawson Creek tributary
Township road
523
T-10
Boundary of low-level radioactive-waste repository site
0 100 200 METERS
0 200 400 600 FEET
EXPLANATION
523 U.S. GEOLOGICAL SURVEY WELL AND NUMBER, JANUARY 1985
150 U.S. ECOLOGY, INCO. WELL AND NUMBER, SEPTEMBER 1985
T-18 BURIAL-TRENCH SUMP AND BURIAL-TRENCH NUMBER

Figure 30. Location of ground-water sampling sites for nonradiological hazardous waste in and near the low-level radioactive-waste repository site near Sheffield, Ill.

Table 9. Concentrations of volatile organic compounds in water from wells in and near the low-level radioactive-waste repository site near Sheffield, Ill., 1985

[NPDES, National Pollutant Discharge Elimination System Program. All concentrations are in micrograms per liter; <, mass spectrometer may have detected the compound at a concentration too small to be quantitated; --, no value measured]

Volatile organic compound	NPDES identification	Well number						
		150	516	523	534	563	574	575
trans 1,3-Dichloropropene	3	--	--	--	--	--	--	<1
Benzene	4	--	85	3	<1	--	--	<1
Carbon tetrachloride	6	6	--	<1	--	--	--	--
Chlorobenzene	7	--	<1	<1	--	--	--	--
1,2-Dichloroethane	10	--	2	2	--	21	--	9
1,1,1-Trichloroethane	11	6	6	[1]>1,000	--	[1]>1,000	6	[1]>1,000
1,1-Dichloroethane	13	--	<1	320	--	89	--	117
1,1,2-Trichloroethane	14	--	--	<1	<1	--	--	<1
1,1,2,2-Tetrachloroethane	15	--	--	<1	--	--	--	--
Chloroform	23	<1	175	209	--	10	--	2
1,1-Dichloroethylene	29	--	--	6	--	--	--	5
1,2-Dichloroethylene	30	<1	2	--	<1	2	--	1
1,2-Dichloropropane	32	--	4	4	--	--	--	--
cis 1,3-Dichloropropene	33	--	--	<1	--	--	--	--
Methylene chloride	44	5	12	7	--	1	1	--
Bromoform	47	--	--	--	--	--	--	--
Bromodichloromethane	48	--	--	--	--	--	--	--
Dibromochloromethane	51	--	--	--	--	--	--	--
Tetrachloroethylene	85	--	[1]>1,000	14	--	--	--	110
Toluene	86	--	<1	<1	<1	--	--	<1
Trichloroethylene	87	--	22	3	<1	--	--	10

[1] These large concentrations exceed the dynamic range of the detector. Estimated 1,1,1-trichloroethane concentrations are 12, 3.2, and 2.5 mg/L for wells 523, 563, and 575, respectively. The estimated tetrachloroethylene concentration for well 516 is 1.4 mg/L.

radioactive waste indicates that ^3H may be an appropriate tracer for detection monitoring to screen for organic contamination at this site.

Contamination from major mixed waste types identified in a survey by the Brookhaven National Laboratory (Bowerman and others, 1985) was not indicated in ground water at the repository site near Sheffield, Ill. Concentrations of the chemicals associated with these waste types—toluene, xylene, lead, and chromium—were less than or equal to detection limits or were similar to background concentrations for the sampled locations.

Repository Site Near Barnwell, South Carolina

The low-level radioactive-waste repository site near Barnwell, S.C. (fig. 1), is an example of an operating commercial low-level radioactive-waste repository site using waste classification, waste segregation, and, to the extent practical, operating procedures required in 10CFR61 (U.S. Nuclear Regulatory Commission, 1982a) for low-level radioactive-waste burial. The site is operated by Chem-Nuclear Systems Inc., and annually it receives about one-half of the Nation's low-level radioactive waste generated by non–Federal facilities. Liquid scintillation vials containing toluene and xylene have not been buried at this site since 1978 (U.S. Nuclear Regulatory Commission, 1982b).

The repository site near Barnwell is underlain by about 320 m of unconsolidated sediments and limestone in the lower part of which is the regional Middendorf aquifer in the Middendorf Formation of Cretaceous age. Ground-water flow in surficial material generally is to the southwest towards Marys Branch Creek, a spring-sustained perennial stream about 1,000 m south-southwest of the closest disposal trench (Cahill, 1982).

Large ^3H concentrations detected in water from a monitoring well, which is 3 m from a burial trench and is screened at a depth of 12 m, have indicated migration of waste from the burial trenches to the shallowest ground water (Cahill, 1982). Czyscinski and Weiss (1981) measured large ^{3}H contents in soil cores more than 3 m below the bottom of burial trenches. More recent data indicate further vertical and horizontal migration of ^{3}H in ground water (Goode, 1986).

Limited ground-water sampling and analysis by personnel from the Brookhaven National Laboratory, the U.S. Geological Survey, the South Carolina Department of Health and Environmental Control, and by the operator have detected concentrations of organic constituents that are greater than background concentrations in and adjacent to burial trenches. Czyscinski and Weiss (1981) reported organic-carbon concentrations in leachate from seven burial trenches that ranged from background concentrations (about 2 mg/L) to 200 mg/L. Weiss and Colombo (1980) reported dissolved organic-carbon concentrations of 11 and 15 mg/L in water from two shallow wells. A preliminary nonradiological ground-water sampling program conducted by the site operator indicated large concentrations of toluene, xylene, and other chemical constituents in water from onsite wells, as discussed below.

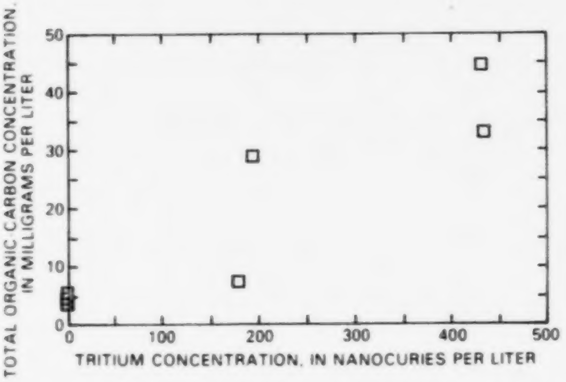

Figure 31. Relation of total organic carbon to tritium for samples from the low-level radioactive-waste repository site near Sheffield, Ill. Organic-chemical concentrations are positively correlated with tritium concentrations at the repository site. Blank squares represent total organic carbon concentration (mg/L) compared with tritium concentrations (nanocuries/L) in water samples. Note: multiple values at 0 tritium concentration appear on vertical axis.

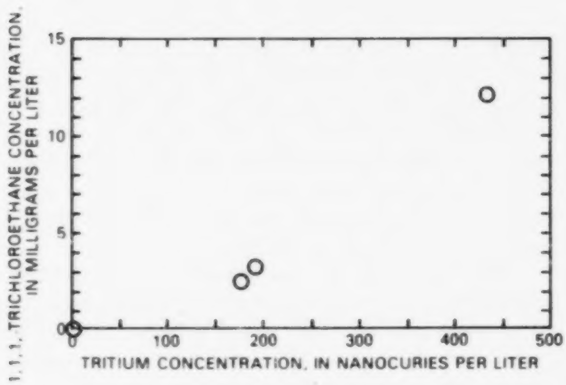

Figure 32. Relation of 1,1,1-trichloroethane to tritium for water samples from the low-level radioactive-waste repository site near Sheffield, Ill. Concentrations of 1,1,1-trichloroethane increase with increasing ^{3}H concentrations for the wells sampled. Blank circles represent 1,1,1 TCE concentration (mg/L) compared with tritium concentration (nanocuries/L) in water samples.

Ground-water quality at the repository site is potentially affected by waste disposal and other activities at the adjacent Savannah River Plant and at the adjacent Allied–General Nuclear Services' nuclear-fuel reprocessing plant, which is not currently (1987) operating.

Five wells on the repository site (fig. 34) were sampled on May 14, 1985, by the Oak Ridge National Laboratory staff, with the assistance of operator personnel. Well WB–0802 is on the eastern site boundary and is upgradient from the burial trenches based on a water-table contour map prepared by Cahill (1982). This well is considered a background sampling location. Well WM–0102 is on the western site boundary and is directly downgradient from the burial trenches. Wells WM–0039 and WM–0074 are adjacent to burial trenches and well WM–0035 is downgradient from well WM–0039. The details of the sampling and analysis procedures and results are presented by Ketelle and others (1986).

Radiation and concentrations of selected radionuclides and of organic-contamination indicators—total organic carbon (TOC) and total organic halogens (TOX)—are listed in table 10. Tritium concentrations indicate migration from the low-level radioactive-waste burial trenches; maximum concentrations were measured in water from well WM–0039 adjacent to burial trench 8. Well WM–0039 is perforated between 17 and 20 m below the surface, in water-yielding zone 2 of Cahill (1982). The ^{3}H concentration is similar to the detection limit of 810 pCi/L at the upgradient boundary well (well WB-0802) and is less than the detection limit at the downgradient boundary well (well WB-0102). Tritium concentrations were consistent with previous recent concentrations indicating that the collected samples are representative of normal ground-water conditions.

In general, water at shallow depths beneath the site is only slightly contaminated. Small concentrations of contaminants and organic-contamination indicators at the boundary of the site indicate that activities at the adjacent facilities have not affected the water beneath the site. Concentrations of cations, anions, and metals were similar at all wells. Chromium concentrations were at the detection limit at wells WM–0074 and WM–0039. Lead concentrations were small with maximum concentrations at wells WM–0074 (0.006 mg/L) and WM–0035 (0.005

mg/L). Nitrate concentrations were maximum at well WB–0102 (16 mg/L), the downgradient well; this maximum may indicate fertilizer application. Notably, the next largest concentration (9 mg/L) was at well WB–0802, the upgradient well. Sulfide, which was less than the detection limit at the upgradient well, was detected in small concentrations at the other wells. The maximum manganese concentrations were at wells WM–0039 (0.017 mg/L) and WM–0035 (0.016 mg/L).

The organic-contamination indicators, TOC and TOX, were small and similar for all sampled wells; concentrations of only a few organic constituents were greater than detection limits (Ketelle and others, 1986). Chloroform was detected in all samples; the maximum concentrations were at wells WM–0074 (0.008 mg/L) and WM–0039 (0.014 and 0.012 mg/L). Tetrachloroethylene was measured at the detection limit in the sample from well WM–0074 and in one of two samples from well WM–0039. Trichloroethylene also was measured at the detection limit in only one of the two samples from well WM–0039. Toluene was not detected in any of the samples. Xylene was not analyzed during this sampling. No other organic constituents were detected at concentrations greater than detection limits. These results indicate that low-level radioactive-waste burial has had a minor effect on the nonradiological quality of onsite ground water.

The sample from well WM–0035 contained hydrocarbons that might be related to petroleum products (Ketelle and others, 1986). Two fuel pumps are located about 15 m to the southwest of well WM–0035, and it is possible that fuel leaking from underground storage tanks migrated to this well owing to heterogeneity of the near-surface geology. Analyses made by the site operator

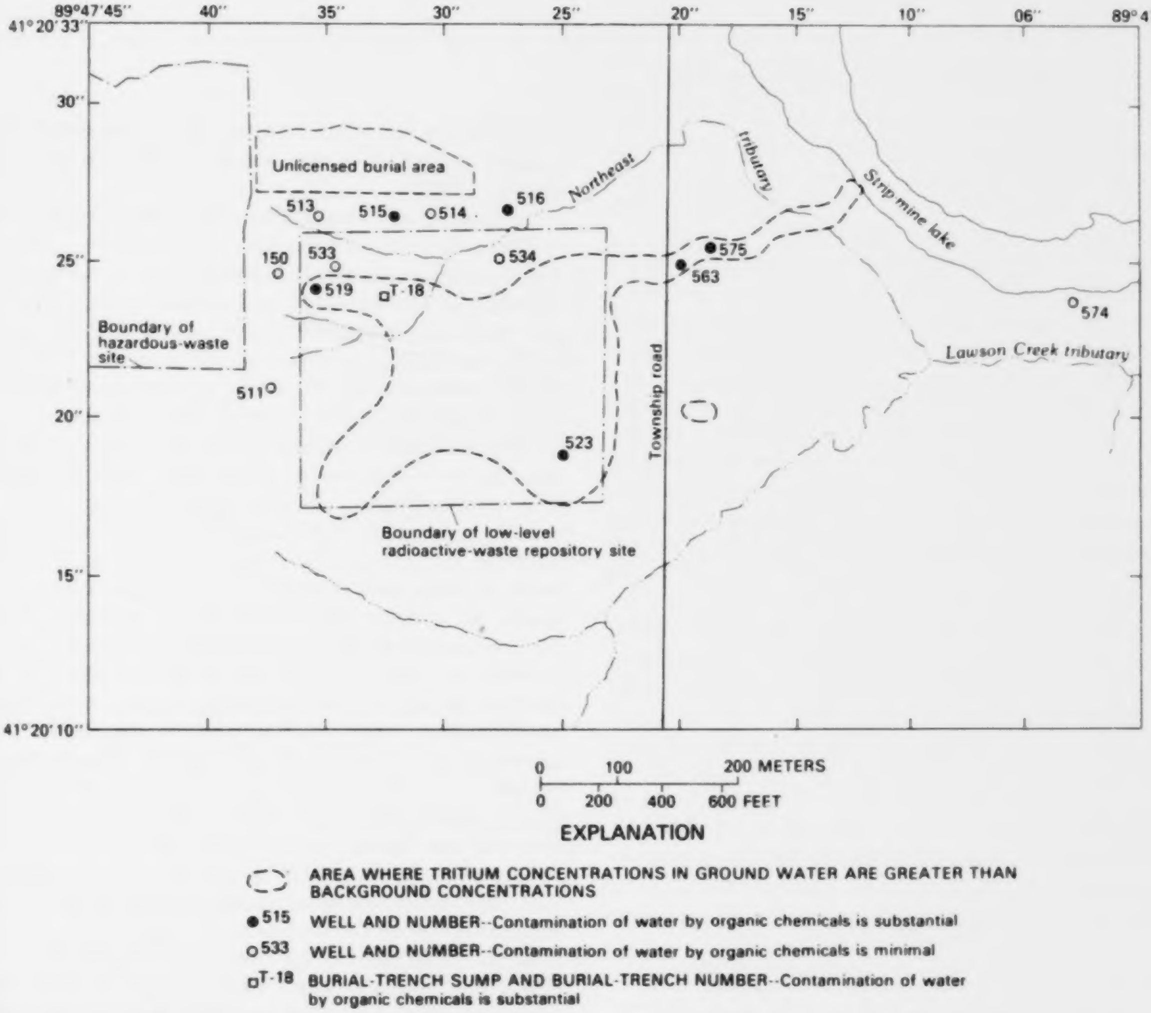
89°47'45"
40"
35"
30"
25"
20"
15"
10"
06"
89°47'
41°20'33"
30"
25"
20"
15"
41°20'10"
Unlicensed burial area
Northeast
tributary
Strip mine lake
513
515
514
516
150
533
534
519
T-18
575
563
574
Boundary of hazardous-waste site
511
523
Township road
Lawson Creek tributary
Boundary of low-level radioactive-waste repository site
0
100
200 METERS
0
200
400
600 FEET
EXPLANATION
AREA WHERE TRITIUM CONCENTRATIONS IN GROUND WATER ARE GREATER THAN BACKGROUND CONCENTRATIONS
515 WELL AND NUMBER--Contamination of water by organic chemicals is substantial
533 WELL AND NUMBER--Contamination of water by organic chemicals is minimal
T-18 BURIAL-TRENCH SUMP AND BURIAL-TRENCH NUMBER--Contamination of water by organic chemicals is substantial

Figure 33. Distribution of tritium and organic-chemical contamination in and near the low-level radioactive-waste repository site near Sheffield, Ill.

Table 10. Radiation and concentrations of selected radionuclides and of organic-contamination indicators in water from wells sampled at the low-level radioactive-waste repository site near Barnwell, S.C.

[pCi/L, picocuries per liter; mg/L, milligrams per liter; µg/L, micrograms per liter; <, less than]

Radiation or radionuclide	Unit of measurement	Well WB-0802	[1]Well WB–0802	Well WM–0074	Well WM–0039	[1]Well WM–0039	Well WM–0035	Well WB–0102
Gross alpha	pCi/L	0.51±2.24	2.16±2.97	2.16±3.24	2.16±2.7	0.92±2.35	16.47±5.94	2.16±2.97
Gross beta	pCi/L	1.62±2.7	4.32±2.97	0.76±2.62	2.7±2.97	1.62±2.7	9.45±3.51	<2.7±2.97
Cesium-137 (^{137}cS)	pCi/L	<13.5	<13.5	<10.8	<8.1	<10.8	<10.8	<10.8
Cobalt-60 (^{60}Co)	pCi/L	<16.2	<13.5	<10.8	<13.5	<13.5	<8.1	<10.8
Tritium (^{3}H)	pCi/L	810±945	1,188±972	2.7E4±1.9E3	2.3E6±8.1E4	2.3E6±8.1E4	1,674±999	<810

Organic-contamination indicator	Unit of measurement	Well WB–0802	[1]Well WB–0802	Well WB–0074	Well WM–0039	[1]Well WM-0039	Well WM–0035	Well WB–0102
Total organic carbon (TOC).	mg/L	0.24	0.54	0.29	0.97	0.91	1.9	0.45
Total organic halogens (TOX).	µg/L	7	10	5	7	7	10	7

[1] Duplicate samples obtained for quality-assurance purposes.

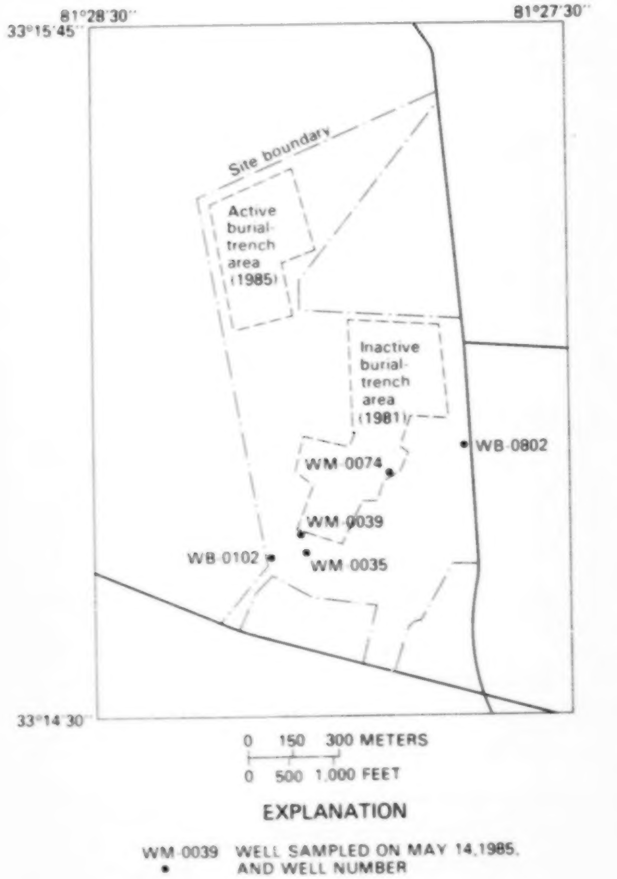

Figure 34. Location of wells sampled at the low-level radioactive-waste repository site near Barnwell, S.C. (modified from Ketelle and others, 1986).

indicated that the relative mixture of hydrocarbon components in this well was similar to that in gasoline (Goode, 1986).

Results of a nonradiological monitoring program by Chem-Nuclear Systems, Inc., at 50 wells in 1982–83 indicate organic chemical contamination at the site. A summary of concentrations of benzene, toluene, xylene, and total volatile organic compounds in samples from wells at the disposal site is presented in table 11 (Goode, 1986). Concentrations of toluene and xylene were maximum at well WM–0035 which, as discussed above, may be contaminated by gasoline. However, these constituents also were detected at several other wells in significant concentrations. Concentrations of total volatile organic compounds were large for several onsite wells. Acetone, chloroform, 1,2-dichloroethane, 1,1,1-trichloroethane, tetrachloroethylene, and isopropanol were detected in greater than background concentrations. Concentrations of individual organic compounds typically were less than 1 mg/L, and several of these were detected at only one or two wells. Organic-constituent concentrations were small at site-boundary wells; the maximum concentration of total volatile organic compounds was 0.011 mg/L, composed entirely of toluene. This contamination may be due to petroleum products. However, the reported occurrence of toluene and xylene at several onsite wells does indicate that these constituents have been released to ground water from the burial trenches, whether the source in the waste is petroleum products (absorbed oil, for example) or liquid-scintillation media buried before 1978. Absence of toluene in samples collected on May 14, 1985, may indicate that variability in site hydrology or source release rates causes transient effects in nonradiological ground-water quality.

Table 11. Concentrations of organic compounds in water from wells sampled in 1982–83 at the low-level radioactive-waste repository site near Barnwell, S.C.

[From Goode (1986). All concentrations in micrograms per liter; <, less than; – –, not reported]

Well	Benzene	Toluene	Xylene	Total volatile organic compounds
WM–0019	8	<1	<1	32
WM–0021	<1	13	<1	30
WM–0022	<1	2	– –	92
WM–0032	<1	2	<1	4
WM–0033	<1	2	2	13
WM–0034	1	7	11	33
WM–0035	<1	70	124	– –
WM–0037	– –	<1	3	– –
WM–0039	8	<1	1	100
WM–0041	2	<1	1	8
WM–0042	<1	<1	<1	6
WM–0043	<1	<1	4	100
WM–0044	3	1	2	60
WM–0045	<1	1	2	22
WM–0046	<1	<1	2	8
WM–0047	<1	<1	2	14
WM–0048	– –	1	1	– –
WM–0049	– –	– –	– –	– –
WM–0050	<1	<1	2	91
WM–0051	1	<1	<1	5
WM–0052	<1	3	<1	20
WM–0054	<1	<1	5	430
WM–0055	<1	5	2	9
WM–0056	<1	8	1	35
WM–0057	<1	<1	<1	14
WM–0070	<1	1	<1	6
WM–0071	<1	1	<1	4
WM–0072	<1	<1	<1	<1
WM–0073	1	2	<1	3
WM–0074	<1	2	<1	26
WM–0075	<1	<1	<1	20
WM–0089	<1	1	<1	40

Available Information from Other Repository Sites

Ground water and burial-trench leachate from the repository sites near West Valley, N.Y., and at Maxey Flats, Ky., have been analyzed for nonradiological hazardous constituents. Dayal and others (1984) summarized geochemical studies at Maxey Flats made by personnel of the Brookhaven National Laboratory from 1976 to 1981. Ground-water and burial-trench samples were analyzed for cations, anions, radionuclides, and organic constituents. However, trace metals, including chromium and lead, were not included in the studies. Organic compounds identified in burial-trench leachates included cresol, cyclohexanone, methyl isobutyl ketone, naphthalene, phenol, toluene, and xylene. Dioxane also was detected in the burial trench leachates although the concentration was not quantified (Czyscinski and Weiss, 1981; Weiss and Colombo, 1980). Previously, researchers of the Brookhaven National Laboratory detected trichloroethane in burial-trench leachate (reported by General Research Corp., 1980). Of these organic compounds, toluene was detected in the largest concentrations, as much as 9.5 mg/L in 1979 (Dayal and others, 1984). Large concentrations of toluene were consistently detected in burial-trench leachates from Maxey Flats. Xylene also was detected often although at concentrations an order of magnitude less than those for toluene. Weiss and Colombo (1980) detected dioxane, naphthalene, toluene, xylene, and other organic compounds in water from one well, and dibutyl phthalate and triphenyl phosphate only in water from another well. Concentrations of dissolved organic carbon in burial trenches decreased during 1976–79 (Czyscinski and Weiss, 1981).

Kirby (1984) presented more recent results (1981–82) from sampling at Maxey Flats. Many of the organic compounds previously identified were not detected in these samples. These results may indicate improved trench-cover effectiveness and subsequent decreases in leaching, or depletion of the source owing to leaching since burial has ceased. On the basis of these data, toluene constitutes the primary hazardous organic constituent detected in ground water and burial-trench leachate at the Maxey Flats site. Toluene concentrations may have decreased to background concentrations owing to transient effects since the cessation of burial operations.

Personnel from the New York State Department of Health and the Brookhaven National Laboratory sampled burial-trench leachate at the repository site near West Valley, N.Y. As for the repository site at Maxey Flats, Ky., no analyses appear to have been made for trace hazardous metals, including chromium and lead. Burial-trench leachates from the repository site near West Valley were analyzed for organic constituents.

Results of the New York State Department of Health's sampling and analysis for organic constituents in burial-trench leachate from the low-level radioactive-waste repository site near West Valley, N.Y., were summarized by Husain and others (1979):

> The major components of the dichloromethane fraction were cresol, aromatic ketones, and xylyl butanoic acid, whereas the hexane fraction was dominated by phthlate ester and tributyl phosphate. Many constituents in the

hexane fraction were likely derived from buried cleaning agents, germicidal cleansers, surfactants, and paints. The aromatic ketones, xylyl butanoic acid, and humic acid residues were probably naturally occurring breakdown products of living matter.

The type and concentrations of organic chemicals identified in the burial-trench leachates were considered to be similar to those in water samples from landfills in Illinois, Pennsylvania, and Wisconsin (Husain and others, 1979).

Leachate samples were collected from six burial trenches at the repository site near West Valley, N.Y. (Weiss and Colombo, 1980). Concentrations of dissolved organic carbon increased in samples from four of these burial trenches from November 1977 through October 1978. Organic chemicals identified in the burial-trench leachates included cresol, dioxane, naphthalene, phenol, and toluene. The concentration of toluene increased at all trenches from November 1977 through October 1978; the maximum concentration was 25 mg/L. Cresol also was present in large concentrations, and phenol concentrations were large in several samples. Xylene, however, was not detected in any burial-trench samples (Weiss and Colombo, 1980).

Summary

Water samples from monitoring wells at the low-level radioactive-waste repository sites near Sheffield, Ill., and near Barnwell, S.C., were analyzed for hazardous organic chemicals, metals, organic-contamination indicators, and general water quality. At the repository site near Sheffield, several typical organic chemicals were detected in concentrations greater than background concentrations in water from onsite wells and in water from an offsite area where ^{3}H concentrations are greater than background concentrations. Contamination of ground water by ^{3}H and organic compounds distinguish the effects of the repository site from those of adjacent hazardous- and industrial-waste burial operations. At the site near Barnwell, only small concentrations of three organic compounds were detected in water from wells adjacent to burial trenches. Hydrocarbons associated with petroleum products were detected at both repository sites. Tritium, which is migrating in small concentrations from burial trenches at both sites, appears to be an appropriate screening tracer for mixed-waste leachate in that organic compounds are detected only in areas where ^{3}H concentrations are greater than background concentrations. Concentrations of hazardous constituents associated with previously identified, major, low-level radioactive, mixed waste types—toluene, xylene, lead, and chromium—were less than or equal to detection limits or similar to background concentrations in all samples. Previously collected data from these sites and other commercially operated low-level radioactive-waste repository sites support the conclusion that organic chemicals are the primary nonradiological contaminants associated with low-level radioactive-waste burial.

Acknowledgements

R.H. Ketelle and other Oak Ridge National Laboratory staff collected and analyzed the samples and assisted in interpreting the results. U.S. Ecology Inc., and Chem-Nuclear Systems Inc., provided access to monitoring wells and onsite equipment; their respective staffs were helpful in all aspects of the study. This paper summarizes the author's investigations during previous employment with the U.S. Nuclear Regulatory Commission; data collected during the study have already been published (Goode, 1986).

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Geohydrology of the Near-Surface Unsaturated Zone Adjacent to the Disposal Site for Low-Level Radioactive Waste near Beatty, Nevada

By Jeffrey M. Fischer

Introduction

Shallow-land burial in arid areas is considered the best method for isolating low-level radioactive waste from the environment (Nichols and Goode, this report; Mercer and others, 1983). A major threat to waste isolation in shallow trenches is ground-water percolation. Repository sites in arid areas are believed to minimize the risk of ground-water contamination because such sites receive minimal precipitation and are underlain by thick unsaturated zones. Unfortunately, few data are available on rates of water percolation in an arid environment.

Low-level radioactive waste has been buried at a repository site near Beatty, Nev., since 1962. To determine the suitability of the site for waste burial and to help develop criteria for future repository-site selection, the U.S. Geological Survey began a study of the hydrology of the repository site near Beatty in 1976. On the basis of the initial study findings (Nichols, 1985), the U.S. Geological Survey began a detailed study of the unsaturated zone near the Beatty site in 1984. The objective of the study was to determine rates and directions of ground-water movement through the 115-m-thick unsaturated zone. The approach was to measure water potential, moisture content, and unsaturated hydraulic conductivity of the thick unsaturated zone and to use Darcy's law to calculate fluxes.

Location and Setting

The low-level radioactive-waste repository site is located in the Amargosa Desert of southern Nevada about 17 km southeast of Beatty and about 170 km northwest of Las Vegas (fig. 35). The Amargosa Desert, a northwest-trending valley within the Basin and Range province, is bounded by block-faulted mountains composed of lower Paleozoic carbonate sediments and Tertiary volcanic rocks. The valley is formed by normal faulting along the mountain fronts. Near the repository site, the valley is 13 km wide. The repository site is underlain by about 170 m of unconsolidated alluvial-fan, fluvial, and playa deposits (Clebsch, 1968), the upper 30 m of which are an unconsolidated mixture of poorly sorted cobbles, gravel, sand, and silt.

The Amargosa Desert is one of the driest areas in the Nation. Mean annual precipitation ranges from 74 mm at Lathrop wells to 114 mm at Beatty. Seasonal and spatial variation can be considerable. Estimates of monthly potential evapotranspiration near Beatty range from 50 mm in January to about 300 mm from May through July (Nichols, 1985). Vegetation in the desert is sparse.

The surface of the Amargosa Valley is almost flat and is dissected by many, small, dry washes. The main drainage, the Amargosa River, an ephemeral stream, is within 3 km of the repository site. The river and many of the small washes in the vicinity of the repository site all drain to the southeast. In most years, there is no flow in these channels. The alluvial fans drain to the southwest 0.5 km from the repository site where the flow reaches a southeast-trending channel.

The saturated flow system beneath the Amargosa Desert is not well understood. It is presumed that a carbonate-rock aquifer underlies most of the northern one-half of the desert (Winograd and Thordarson, 1975). Ground-water levels in the vicinity of the repository site indicate the ground-water gradient in the local area is to the south-southwest. Depth to water at the repository site ranges from 85 to 115 m.

The unsaturated zone near the repository site is composed of alluvial-fan, fluvial, and playa deposits. Surficial deposits are eolian and about 0.5 m thick. Unconsolidated gravelly to cobbly sands underlie the eolian deposits to a depth of 65 m. Within the cobbly sands is a gravelly cobble layer, with little sand, that extends from 6 to 9 m below the land surface. Below a depth of 65 m, well logs indicate a thin caliche layer above a 15-m-thick clay (playa) deposit. Below a depth of 90 m, alternating layers of clean and muddy sands predominate down to the water table.

Data Collection

The dry and stony alluvium at the study site is difficult to sample and instrument. Thermocouple psychrometers are the only instrument available for measuring water potential in such an arid environment

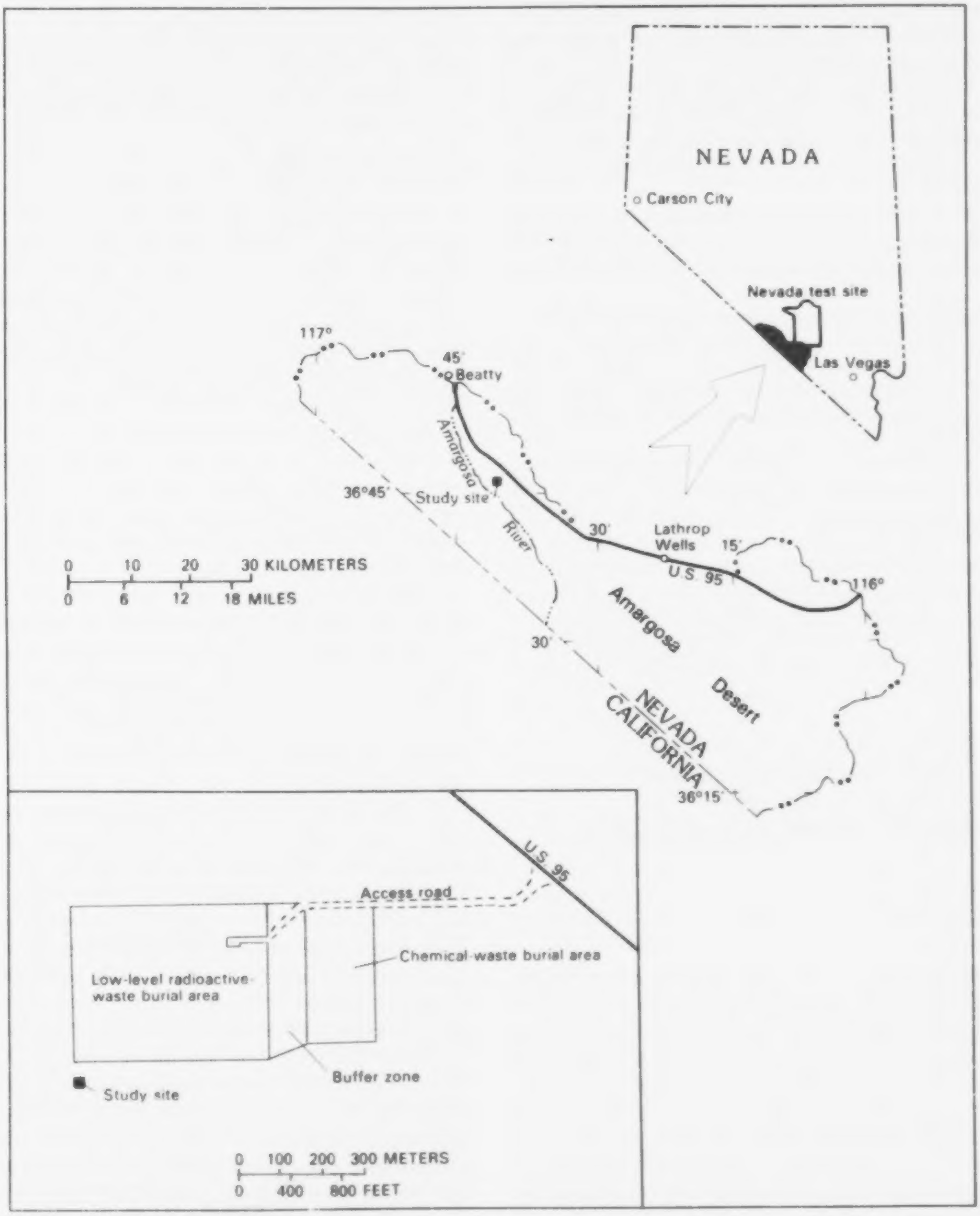
NEVADA
Carson City
Nevada test site
Las Vegas
117°
45'
Beatty
Amargosa River
36°45'
Study site
30'
Lathrop Wells
15'
U.S. 95
116°
Amargosa Desert
30'
NEVADA
CALIFORNIA
36°15'
0 10 20 30 KILOMETERS
0 6 12 18 MILES
U.S. 95
Access road
Chemical-waste burial area
Low-level radioactive-waste burial area
Buffer zone
Study site
0 100 200 300 METERS
0 400 800 FEET

Figure 35. Location of study site near the low-level radioactive-waste repository site near Beatty, Nev.

(Moore and Caldwell, 1972). At the study site, psychrometers were installed at depths greater than 3 m to avoid the shallow zone where water potentials vary on a daily basis. The psychrometer measurements should provide a basis for estimating long-term average recharge.

A vertical monitoring shaft was installed near the southwest corner of the low-level radioactive-waste repository site in 1983 (fig. 35). The shaft is 1.52 m in diameter and penetrates 14 m of alluvium. Because of safety concerns the shaft was located offsite. Starting in 1984, laboratory-calibrated psychrometers (Brown and Bartos, 1982) were installed in access holes drilled 4 m laterally out from the wall of the shaft. The method of installation allows for retrieval and recalibration of the psychrometers after extended periods (Morgan and Fischer, 1984). Initial installation of psychrometers was limited to a depth of 7 m to test the installation procedure. Instrumentation of the entire shaft was completed in 1986. A data logger is used to collect water-potential data daily.

Moisture content of the alluvium is measured with a neutron moisture probe. Neutron access tubes were installed during 1984 to a depth of 31 m, using the ODEX method. The neutron moisture probe was calibrated with samples collected during installation of the neutron access tubes. Samples collected during installation of the neutron access tubes also are being used to determine hydraulic properties of the alluvium. Moisture-content measurements are made each month and more frequently during periods when precipitation is sufficient to result in infiltration.

A weather station was installed at the study site in 1983 to monitor solar radiation, wind speed, relative humidity, air temperature, and precipitation. Weather data are collected hourly.

Results to Data

Precipitation has been minimal since the start of the study. Measured precipitation since 1984 has totaled 165 mm. Of this total, 54 mm has fallen from January through June 1987. No precipitation during a 24-hour period has exceeded 23 mm. About 80 percent of the measured precipitation occurred from November through March. Measured monthly potential evapotranspiration has ranged from 3 mm in the winter to 270 mm in the summer.

Depth of water penetration, as measured in the neutron access tubes, has been less than 2 m. Below a depth of 2 m, moisture-content measurements varied little from July 1986 through April 1987 (fig. 36). Moisture content generally ranged from 2 to 8 percent on a gravimetric basis. In the upper 1.5 m of alluvium, moisture content ranged from almost zero during the summer to 10 percent after it rained. At depth of 8 to 11 m, a zone of minimal moisture (2 to 4 percent) is present below the cobble layer. Greater than average moisture content is present at depths of 7 and 14 m (fig. 36).

Water potential measured during the study had a range of -3.1×10^6 to -5.5×10^6 Pa (−31 to −55 bars). Previous studies (Isaacson and others, 1974) have indicated that a significant part of water movement at these small values of water potential may be in the form of water vapor. Temperature gradients affect water-vapor movement to a much greater extent than do water-potential gradients. Temperature measurements at Beatty indicate that water-vapor movement may be substantial above a depth of 8 m because temperature gradients are steep. Temperature gradients have a seasonal variation and produce upward water-vapor movement from June through November and downward vapor movement from December through May. Water-vapor movement probably is not significant below 8 m because yearly temperature variations are less than 0.5 °C.

Water-potential measurements at depths from 3 to 5 m have a yearly sinusoidal variation that is attenuated with depth. Water potential at a depth of 3 m ranged from -4.0×10^6 to -5.5×10^6 Pa (−40 to −55 bars) whereas water potential at a depth of 5 m ranged from -4.3×10^6 to -4.8×10^6 Pa (−43 to −48 bars) (fig. 36). The occurrence of maximum and minimum values are offset at depth; at a depth of 3 m the minimum occurred in January, whereas at a depth of 5 m, the minimum occurred in April. Periods of maximum changes in water potential seem to be related to periods of maximum temperature gradients and water-vapor movement. For most of the year, the gradient in this zone was upward towards the land surface, although the gradient usually is downward from March through May.

Water-potential measurements below a depth of 6 m had only minor seasonal variations and ranged from -3.1×10^6 to -4.7×10^6 Pa (−31 to −47 bars). The gravel layer, at a depth of 7 to 9 m, appears to have some effect on the water potential, possibly because it lacks fine-grained material that can hold water at such small values of water potential. The gradient in the depth interval of 5 to 7 m is about 5×10^5 Pa/m (5 bars/m) downward, whereas the gradient in the depth interval of 7 to 9 m is almost zero (fig. 36). Below the cobble layer, from a depth of 9 to 13 m, a steady upward gradient of 3.3×10^5 Pa/m (3.3 bars/m) was measured (fig. 36). Water-potential measurements in the depth interval from 10 to 11 m are uncertain because either the psychrometers were not installed properly or the water potential exceeded the calibration range of the instruments.

Measurements of the hydraulic properties of the alluvium have not been completed. Laboratory analysis of core samples indicates that the sediments are dense (dry bulk densities of about 2 g/cm^3), very coarse, silty sands. The sediments retain little moisture at small values of water potential and range in porosity from 19 to 27 percent. The current emphasis of the project is to complete measurements of unsaturated hydraulic conductivity and air permeability of the sediments. Such measurements also will indicate how much flow may occur as water vapor and how much may occur as liquid flow through interconnected pore spaces. The latter type of flow has greater potential for causing contamination because it can transport dissolved constituents. Water-vapor flow can only transport isotopes of hydrogen, oxygen, and carbon.

Because the present study is only investigating natural flux rates through the undisturbed alluvium, an additional study is being initiated to determine how waste burial trenches may modify rates and directions of water movement. This new study will investigate how the unlayered, homogenized, and uncompacted sediments used as backfill in the burial trenches modify hydraulic conductivity and hydraulic gradients measured in the natural sediments. Also of interest will be the compaction occurring in the trenches. Psychrometers also may be installed deeper than in the present study to determine if and at what depth water begins to percolate downward towards the water table.

Summary

Measurements made adjacent to the low-level radioactive-waste repository site near Beatty, Nev., indicate that little recharge currently (1987) is moving through

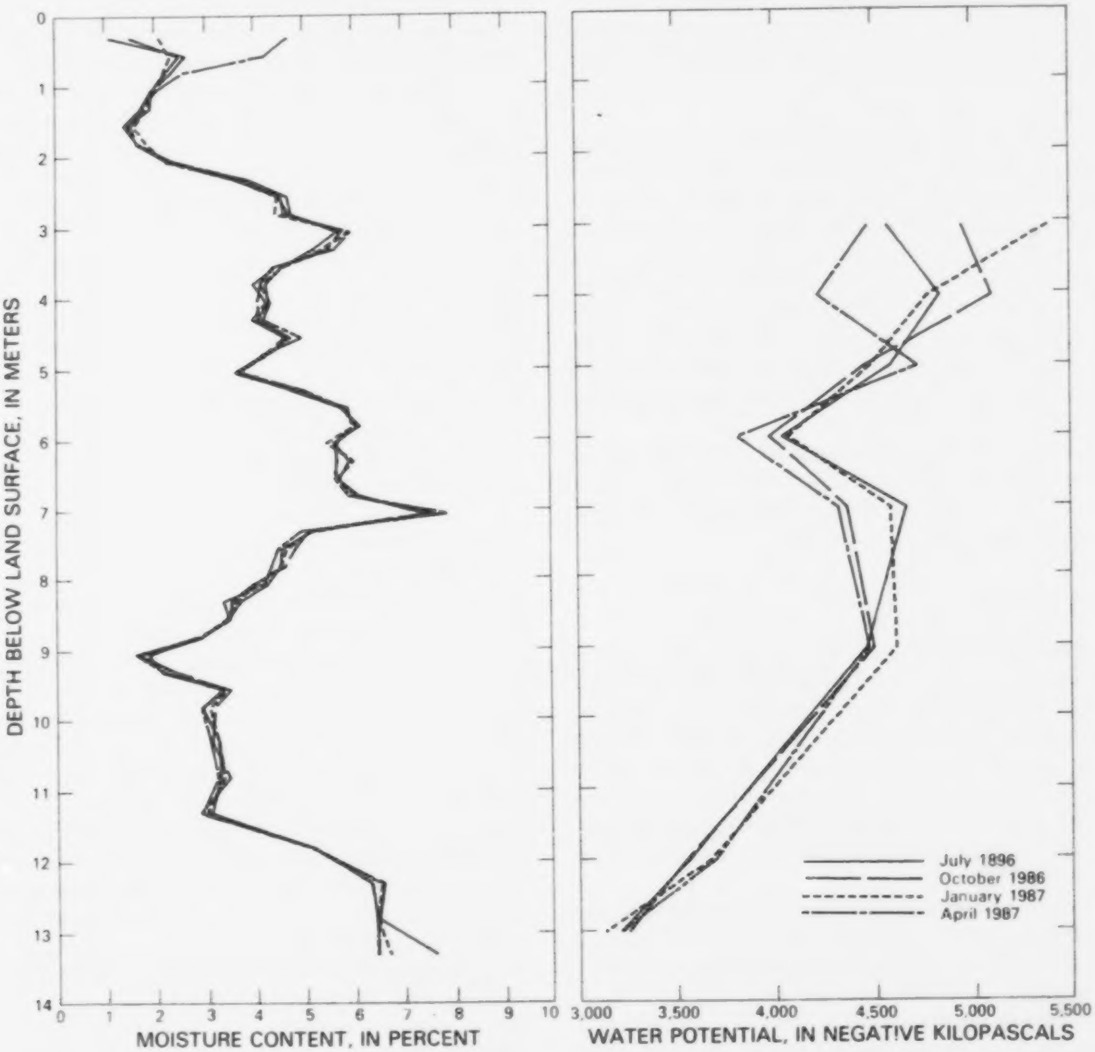

Figure 36. Comparison of moisture content and water potential with depth at the study site near the low-level radioactive-waste repository site near Beatty, Nev. Below a depth of 2 m, moisture-content measurements varied little from July 1986 through April 1987. Water potential measured during the study had a range of -3.1×10^6 to -5.5×10^6 Pa (−31 to −55 bars).

the undisturbed alluvium. Precipitation during the 3 years of the study has totaled 165 mm; precipitation has not penetrated deeper than 2 m. Monthly potential evapotranspiration rates have ranged from 3 to 27 cm. Generally, the hydraulic gradient indicates upward movement of water toward the land surface although the gradient is reversed at depths from 5 to 7 m. Seasonal variations of the water potential and seasonal reversals of the hydraulic gradient occur to a depth of 8 m. Water-vapor movement in response to temperature gradients also may be substantial at depths from 3 to 8 m. Hydraulic-gradient measurements and moisture-content measurements indicate that some water is stored at the top of the cobble layer at a depth of 7 m. Seasonal variations in water potential do not seem to occur below the cobble layer at a depth of 9 m, and the hydraulic gradient indicates upward movement of soil moisture.

Data collected during 1984–87 adjacent to the low-level radioactive-waste repository site near Beatty indicate that the potential for contaminant transport through the undisturbed alluvium is minimal. Much of the flow actually may occur as water vapor that does not transport dissolved constituents. Water-potential gradients indicate that flow through interconnected pore spaces moves toward the land surface. What is not currently (1987) understood is how much precipitation would be needed to reverse the measured gradients. Laboratory measurements indicate that the unsaturated hydraulic conductivity and water potential change rapidly in response to increasing moisture content. A moderate-size rainstorm in early spring, when gradients are lowest, could produce recharge. The clay zone at a depth of 70 m would slow contaminant movement if recharge were to occur. Future study at the site will address the question as to how the burial trenches may modify the natural flow system.

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Some Preliminary Model Studies of Capillary Barriers

By Joe E. Reed

Introduction

The concept of capillary barriers depends on the differing relations for different materials between unsaturated hydraulic conductivity and moisture content in the unsaturated zone. Coarse-grained porous media usually have smaller values of unsaturated hydraulic conductivity at large values of moisture tension (large negative pressures expressed as a water column) than do fine-grained porous media. This is the reverse of the relation at or near saturation. The rationale of capillary barriers is to exploit this phenomenon of the unsaturated zone by replacing the native medium.

Physical Concepts

Relative hydraulic conductivity is defined as the ratio of unsaturated hydraulic conductivity to saturated hydraulic conductivity:

$$K_r = K_u / K_s \tag{1}$$

where

K_r is relative hydraulic conductivity, L^0;
K_u is unsaturated hydraulic conductivity, L^1T^{-1}; and
K_s is saturated hydraulic conductivity, L^1T^{-1}.

A relation between relative hydraulic conductivity and moisture tension was suggested by Gardner (1964, cited in Ripple and others, 1972, p. A6) as:

$$K_r = 1/(1 + (T/T_{1/2})^n \quad (2)$$

where

T is moisture tension, L^1;

$T_{1/2}$ is the moisture tension at which $K_r = 1/2$, L^1; and

n is a fitting parameter, usually ranging from 2 for clay to 5 for sand, L^0.

The relative saturation of porous material is expressed as a fraction of total drainable pore space by:

$$\Phi = (\theta_1 - \theta_0)/(1 - \theta_0) \quad (3)$$

where

Φ is relative saturation, L^0;

θ_1 is water content as a fraction of pore space, L^0; and

θ_0 is residual water content (immobile water) as a fraction of pore space, L^0.

A relation between relative hydraulic conductivity and relative saturation throughout the range of Φ in which Φ is linearly related to $1/T^2$ is (Stallman, 1964):

$$K_r = \Phi^4. \quad (4)$$

The following three hypothetical examples of porous media are used in the model examples:

Lithology	K_S (meters per day)	Porosity	$T_{1/2}$ (meters)	θ_0	n
Clay	3×10^{-5}	0.5	15	0.3	2
Silty sand	3×10^{-3}	.4	1.5	.1	4
Sand	3×10^{-1}	.3	.6	.05	5

The relation of relative hydraulic conductivity and water content to moisture tension for these three types of porous media is shown in figure 37.

Flow Relations

Steady two-dimensional flow is described by:

$$\partial(K_u \partial h/\partial x)/\partial x + \partial(K_u \partial h/\partial z)/\partial z = 0 \quad (5)$$

where

∂ is the partial differentiation operator;

h is hydraulic head, L^1;

x is the horizontal coordinate, L^1; and

z is the vertical coordinate, positive upward, L^1.

If hysteresis can be ignored, then K_u may be expressed as a function of T and, because $h=z-T$, the steady differential equation becomes:

$$\partial(K_u \partial T/\partial x)/\partial x + \partial(K_u(\partial T/\partial z - 1))/\partial z = 0. \quad (6)$$

For vertical flow only, the above equation may be integrated and becomes an expression for the steady flux:

$$K_u(\delta T/\partial z - 1) = K_u(T_u)\left(\left[\frac{\delta T}{\partial x}\right]_{z=z_b} - 1\right) = -q \quad (7)$$

where q is the specific discharge, positive for recharge, L^1T^{-1}, and z_b and T_b represent boundary values, both either at the top or the bottom. The above equation may be integrated a second time to give a general solution for the equation of steady vertical flow as the integral (Ripple and others, 1972, eq. 12):

$$z - z_b = \int_{T_b}^{T} 1/(1 - q/K_u)\,dT. \quad (8)$$

Curves of T versus z for recharge, calculated using the above integral, show T increasing upward but approaching asymptotically a line where $\delta T/\partial z = 0$ and T is such that $K_u(T) = q$. Examples of such curves are shown in Stallman and Reed (1968, fig. 40).

Flow Model

The two-dimensional finite-difference model represents steady-state flow through a vertical section. The model utilizes a rectangular point-distributed grid of a type discussed in Cooley and Naff (1985). This type of grid has the nodes (points of discretized hydraulic head) at the corners of the rectangular blocks (regions of discretized media properties). Relative hydraulic conductivity and saturation are determined for each block in the model by the average of the moisture tensions for the four nodes and by media properties for the block.

The solution technique used was a direct solution algorithm for hydraulic head, within an iterative adjustment for hydraulic conductivity based on previously computed hydraulic head. Changes in hydraulic conductivity between iterations were constrained to be small. Solution by this method required 100 to 200 iterations. Convergence, or divergence, was indicated by maximum hydraulic-head change between iterations, maximum flow residual, and flow balance for the model.

Flow Simulations

The model was used to evaluate a vertical section 732 m wide and 146 m deep, composed of clay (see preceding list for media properties) surrounding a central repository filled with sand, 244 m wide by 49 m deep in profile. Boundary conditions were specified as the same constant for moisture tension on the upper and lower surfaces of the model and no flow through the sides. Thus, the model represents part of a thick unsaturated zone that is situated a sufficient distance above the water table for the boundary conditions to apply. Model simulations were made for four different boundary tensions. Simulated results are shown in figures 38 and 39 for the four boundary tensions of 15 m (model 1), 30 m (model 2), 61 m (model 3), and 91 m (model 4).

There are nine flow lines indicated in figures 38 and 39. These consist of four sets of paired flow lines enclosing one central flow line. Paired flow lines enclose a proportion of the total flow that moves through the clay in the vicinity of the repository. The proportion decreases from 0.2, 0.1, 0.02, to 0.002 as the paired flow lines approach the central flow line. In model 1 (figs. 38 and 39), the flow lines change little in the repository. For this model, the hydraulic conductivity of the sand is about the same as that of the clay. In model 2 (figs. 38 and 39), the flow lines are vertical through the upper part of the repository, but diverge around an area of lesser hydraulic conductivity at the base of the sand. In models 3 and 4 (figs. 38 and 39), flow lines are diverted around the repository by the lesser hydraulic conductivity of the sand.

The location of the repository is evident for all simulated results in figure 39 because the water content is much less in the sand where the sand contacts the clay.

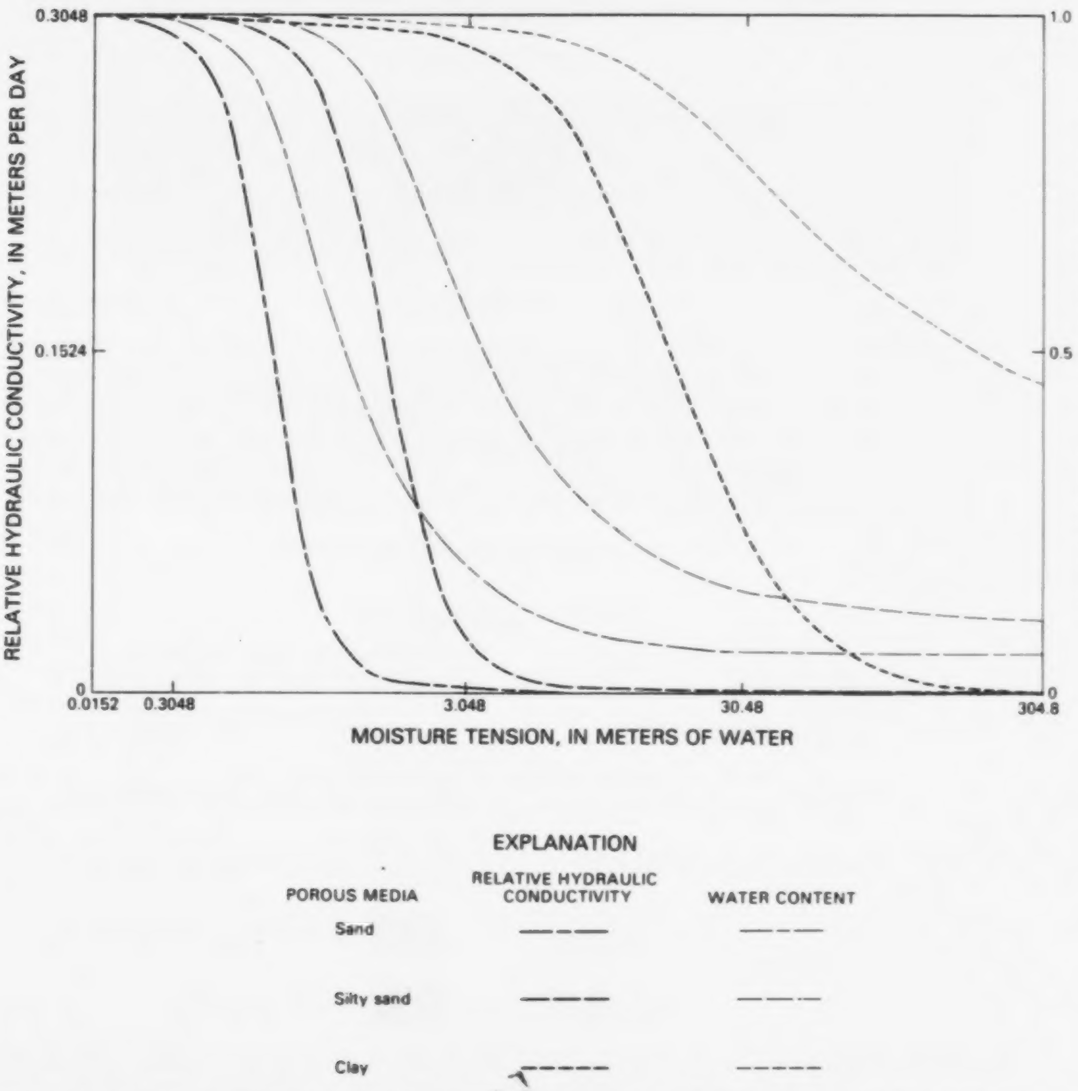

Figure 37. Relation of relative hydraulic conductivity and water content to moisture tension for three hypothetical examples of porous media, sand, silty sand, and clay.

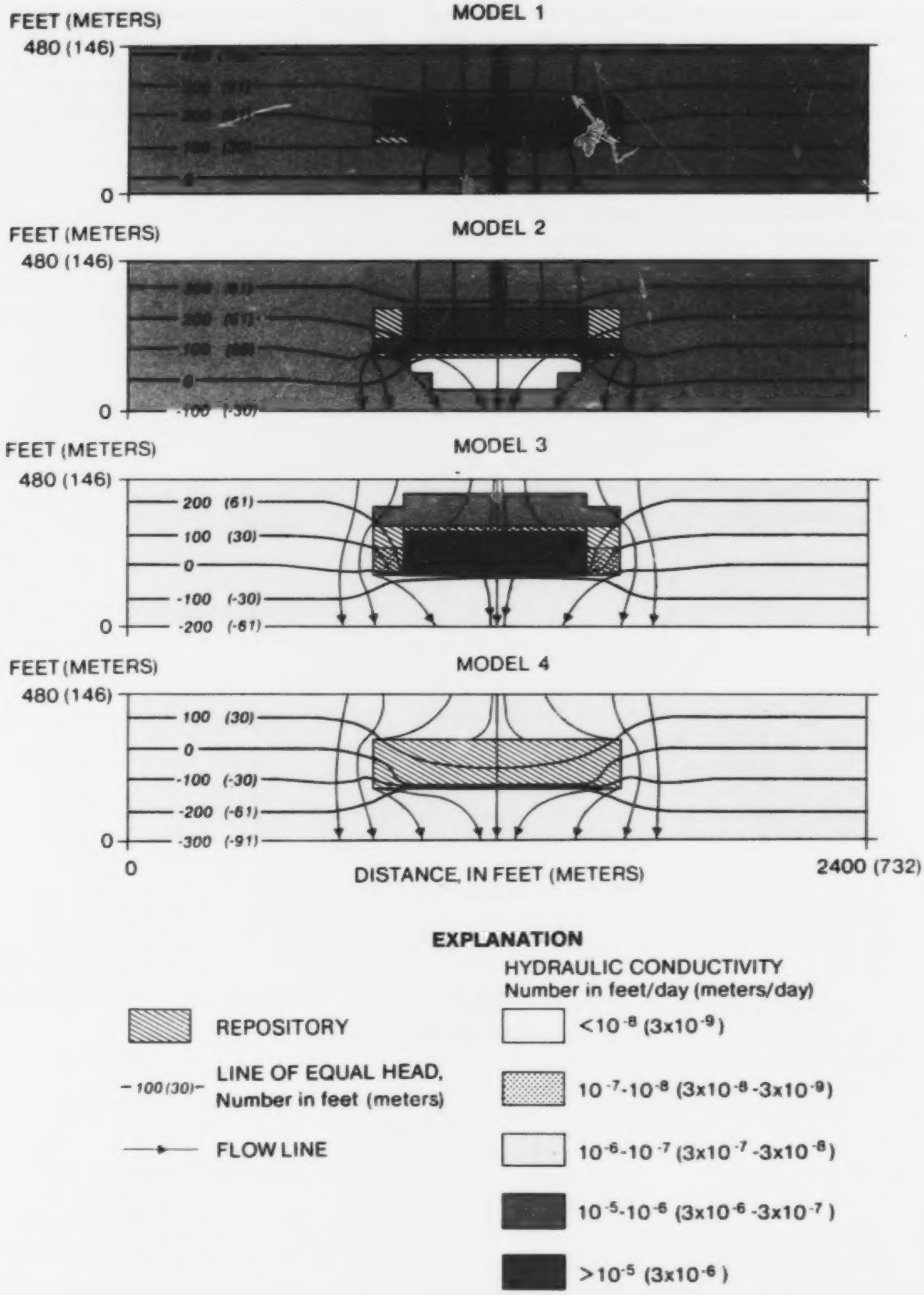
MODEL 1
FEET (METERS)
480 (146)
300 (91)
200 (61)
100 (30)
0
0
MODEL 2
FEET (METERS)
480 (146)
300 (91)
200 (61)
100 (30)
0
-100 (-30)
0
MODEL 3
FEET (METERS)
480 (146)
200 (61)
100 (30)
0
-100 (-30)
-200 (-61)
0
MODEL 4
FEET (METERS)
480 (146)
100 (30)
0
-100 (-30)
-200 (-61)
-300 (-91)
0
0
DISTANCE, IN FEET (METERS)
2400 (732)
EXPLANATION
REPOSITORY
-100(30)- LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
HYDRAULIC CONDUCTIVITY
Number in feet/day (meters/day)
<10 -8 (3x10 -9)
10 -7-10 -8 (3x10 -8 -3x10 -9)
10 -6-10 -7 (3x10 -7 -3x10 -8)
10 -5-10 -6 (3x10 -6 -3x10 -7)
>10 -5 (3x10 -6)

Figure 38. Unsaturated hydraulic conductivity, flow lines, and lines of equal hydraulic head for simulated results with different boundary moisture tensions: Model 1, 15 m; model 2, 30 m; model 3, 61 m; and model 4, 91 m. In models 3 and 4, flow lines are diverted around the repository by the lesser hydraulic conductivity of the sand (also, see fig. 39).

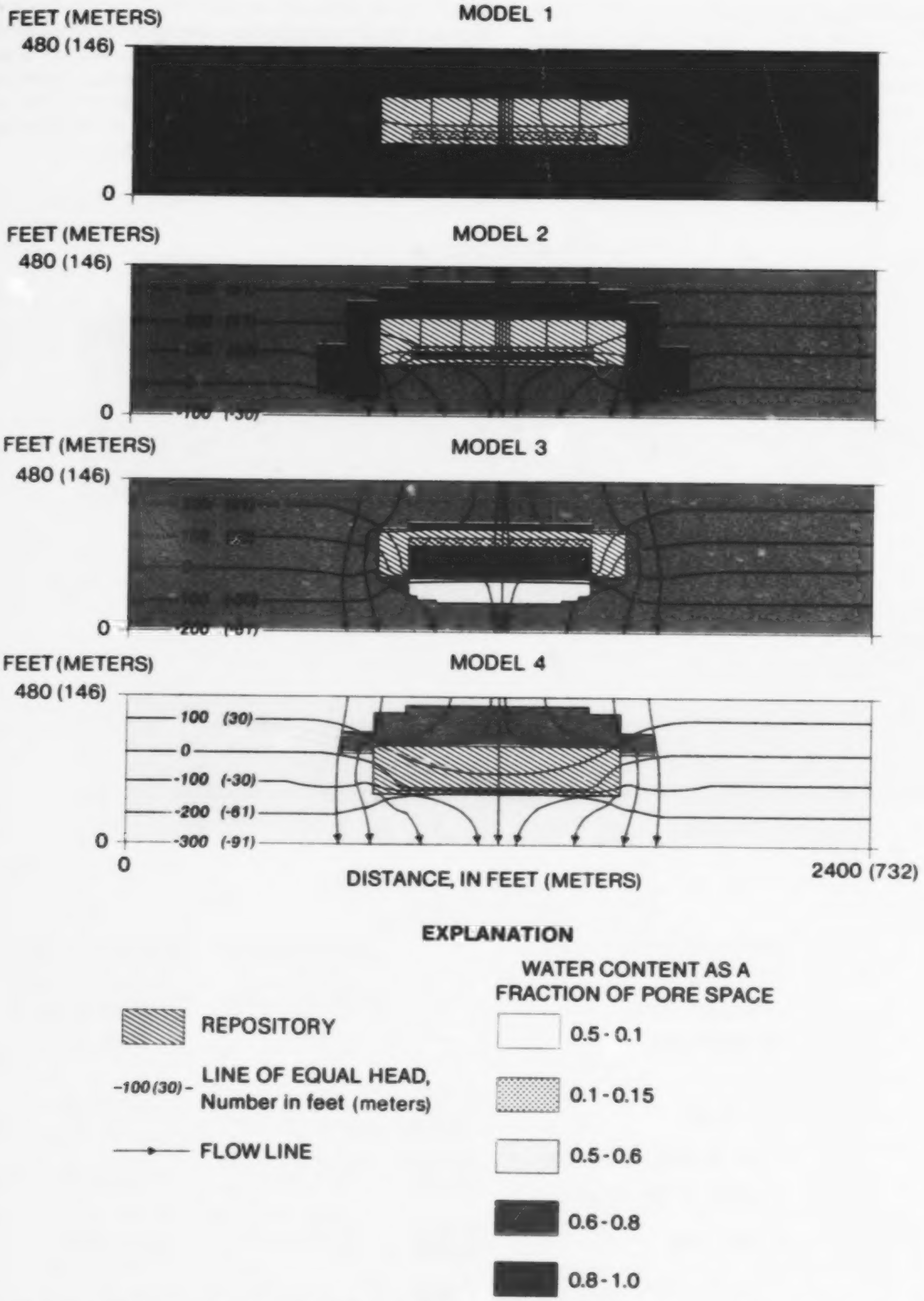
MODEL 1
FEET (METERS)
480 (146)
0
MODEL 2
FEET (METERS)
480 (146)
0
-100 (-30)
MODEL 3
FEET (METERS)
480 (146)
0
-200 (-61)
MODEL 4
FEET (METERS)
480 (146)
100 (30)
0
-100 (-30)
-200 (-61)
-300 (-91)
0
0
DISTANCE, IN FEET (METERS)
2400 (732)
EXPLANATION
REPOSITORY
-100 (30) - LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
WATER CONTENT AS A FRACTION OF PORE SPACE
0.5 - 0.1
0.1 - 0.15
0.5 - 0.6
0.6 - 0.8
0.8 - 1.0

Figure 39. Water content, flow lines, and lines of equal hydraulic head for simulated results with different boundary moisture tensions: Model 1, 15 m; model 2, 30 m; model 3, 61 m; and model 4, 91 m.

Only in model 4 of figure 38, the solution for a boundary tension of 91 m, is the hydraulic conductivity for all the sand less than that for any of the clay. A curious feature of the simulated results is the distribution of water content and resulting hydraulic conductivity within the sand. The hydraulic-head change between iterations and flow imbalances are both small. However, the procedure for calculating hydraulic conductivity for blocks containing a surface tension of zero needs to be improved. Such improvement could change the results for model 3 (figs. 38 and 39) that is the only model containing a moisture tension of zero. Also, there is a possible error due to block size. These model results need to be recomputed using smaller block sizes to evaluate such errors.

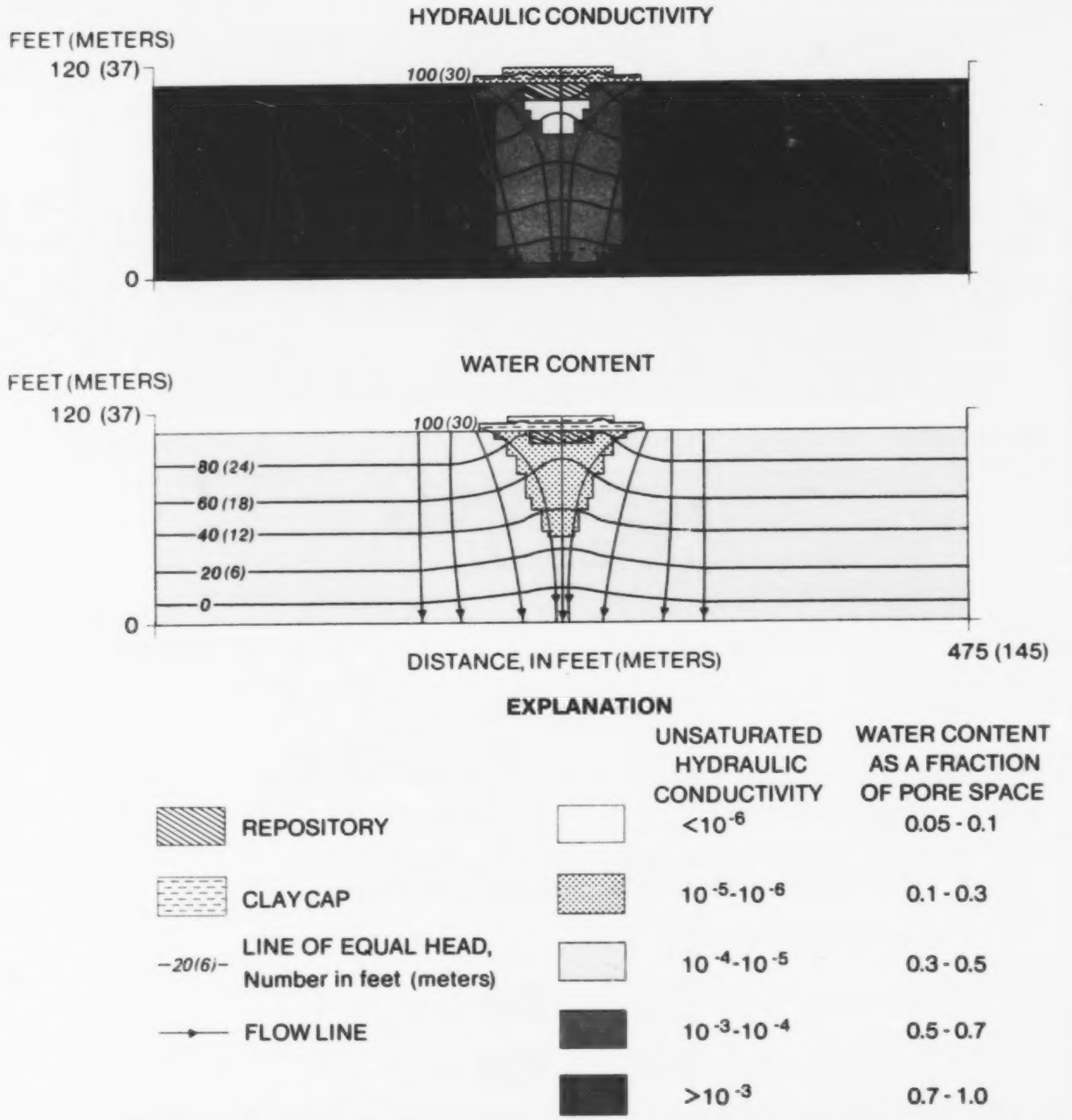
HYDRAULIC CONDUCTIVITY
FEET (METERS)
120 (37)
100 (30)
0
WATER CONTENT
FEET (METERS)
120 (37)
100 (30)
80 (24)
60 (18)
40 (12)
20 (6)
0
0
DISTANCE, IN FEET (METERS)
475 (145)
EXPLANATION
REPOSITORY
CLAY CAP
-20(6)- LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
UNSATURATED HYDRAULIC CONDUCTIVITY
WATER CONTENT AS A FRACTION OF PORE SPACE
<10^-6 0.05 - 0.1
10^-5-10^-6 0.1 - 0.3
10^-4-10^-5 0.3 - 0.5
10^-3-10^-4 0.5 - 0.7
>10^-3 0.7 - 1.0

Figure 40. Unsaturated hydraulic conductivity, water content, flow lines, and lines of equal hydraulic head for a boundary moisture tension of 4 m and a vertical thickness of 37 m: *A*, Unsaturated hydraulic conductivity; and *B*, Water content.

The model then was used to simulate a shallow trench in a native medium of silty clay. The trench, 3 m deep by 12 m wide, is filled with sand and is covered with 3 m of clay. The overall width of the model is 145 m. Results for the simulation using a moisture tension of 4 m at the upper and lower boundaries and a vertical

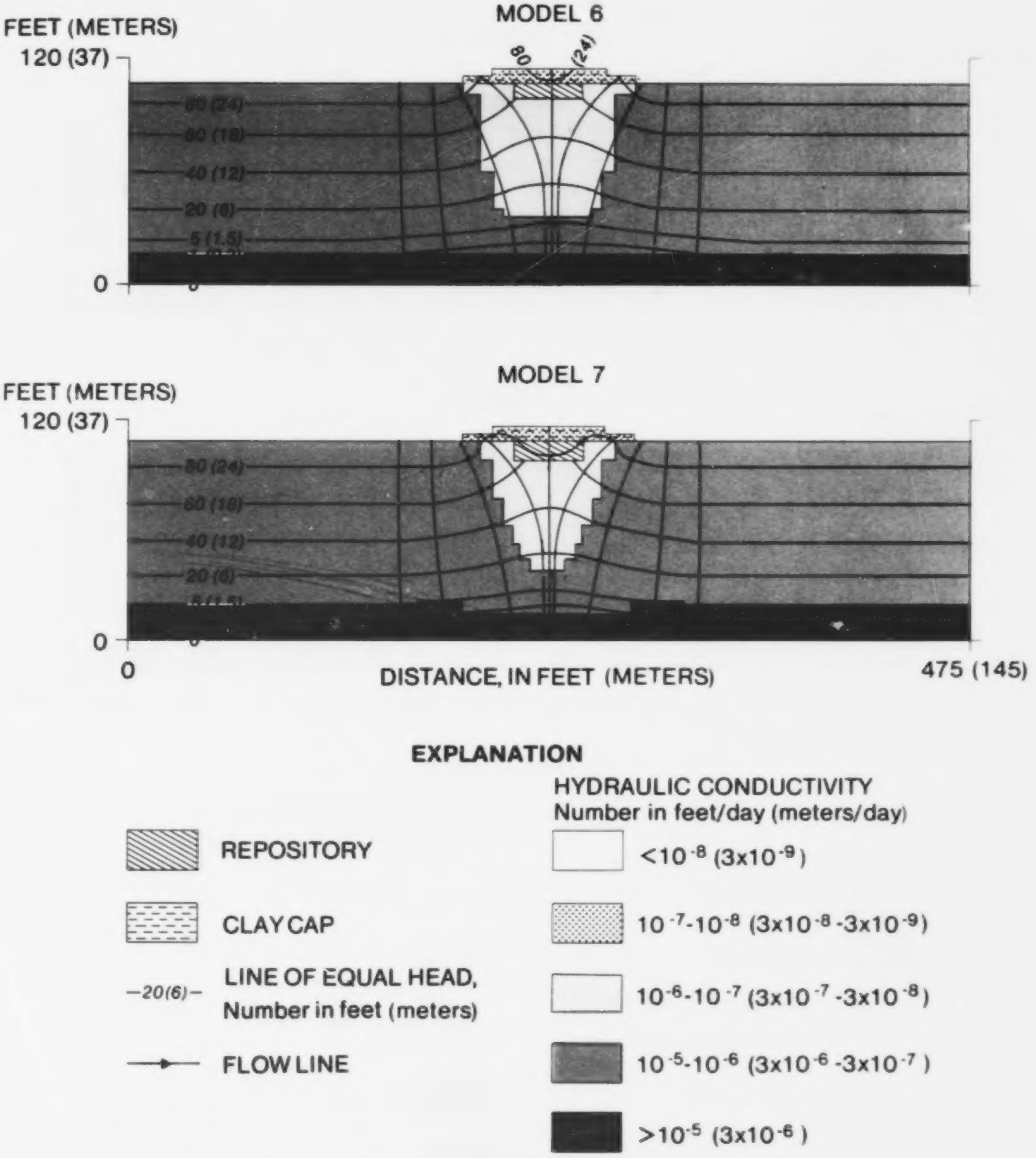
MODEL 6
FEET (METERS)
120 (37)
80
(24)
80 (24)
60 (18)
40 (12)
20 (6)
5 (1.5)
0
MODEL 7
FEET (METERS)
120 (37)
80 (24)
60 (18)
40 (12)
20 (6)
5 (1.5)
0
0
DISTANCE, IN FEET (METERS)
475 (145)
EXPLANATION
REPOSITORY
CLAY CAP
—20(6)— LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
HYDRAULIC CONDUCTIVITY
Number in feet/day (meters/day)
<10-8 (3x10-9)
10-7-10-8 (3x10-8-3x10-9)
10-6-10-7 (3x10-7-3x10-8)
10-5-10-6 (3x10-6-3x10-7)
>10-5 (3x10-6)

Figure 41. Unsaturated hydraulic conductivity, flow lines, and lines of equal hydraulic head: Model 6, infiltration of 38 and 0.38 mm per year for silty sand and clay, respectively; and model 7, infiltration of 76 and 0.76 mm per year for silty sand and clay, respectively.

thickness of 37 m are shown in figure 40. Inflow per unit area, at the top, ranges from 300 to 400 mm/yr along the silty sand and from 1 to 5 mm/yr along the clay.

The model then was used to simulate the same physical geometry but with different boundary conditions. The base of the modeled area is specified as zero tension (water table), and specifying inflow at the top instead of moisture tension. Simulated results are shown for model 6 in figures 41 and 42 for inflow rates of 38 and 0.38 mm/yr for silty sand and clay, respectively. Simulat-

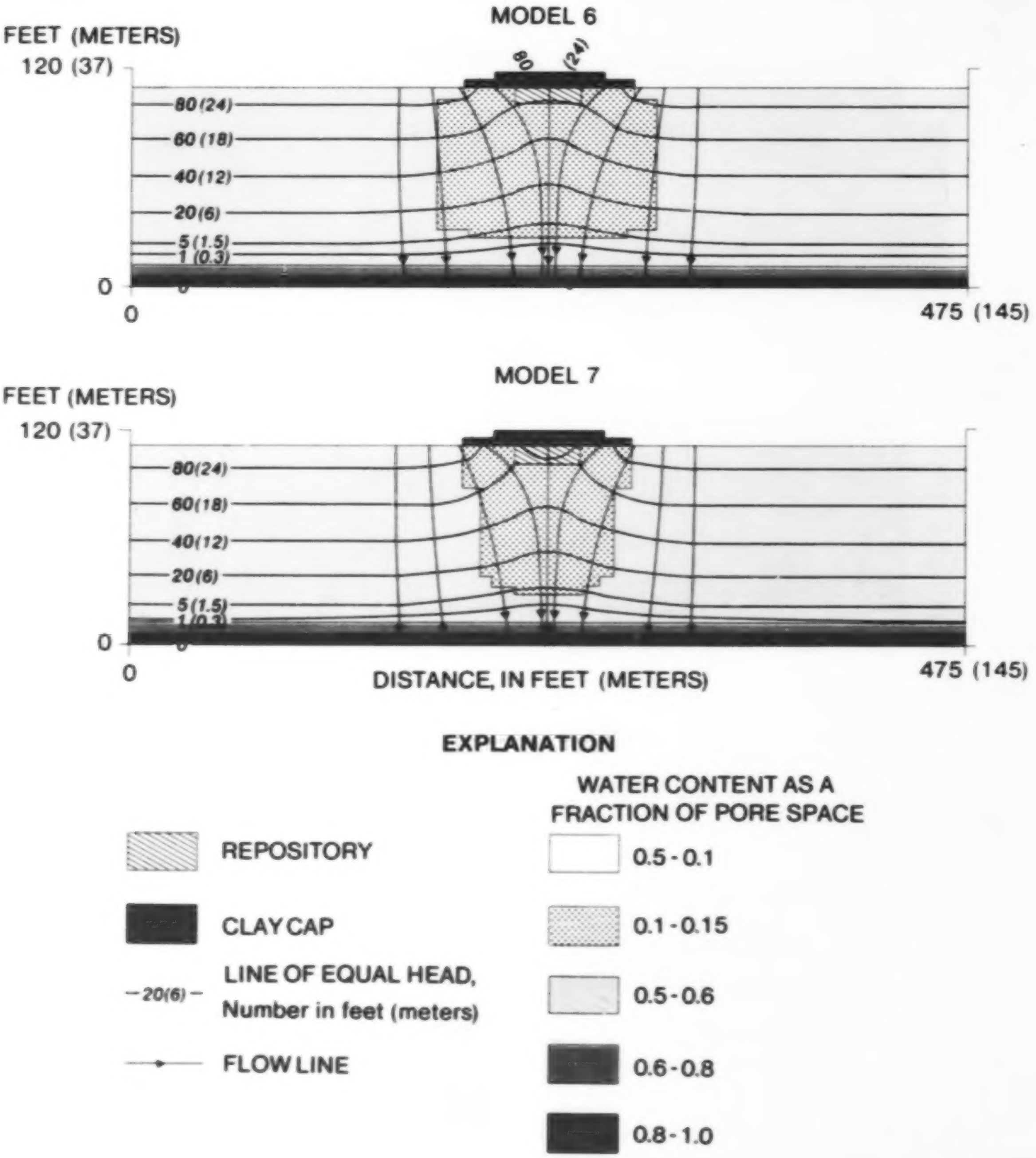
MODEL 6
FEET (METERS)
120 (37)
80 (24)
80(24)
60 (18)
40(12)
20(6)
5(1.5)
1 (0.3)
0
0
475 (145)
MODEL 7
FEET (METERS)
120 (37)
80(24)
60(18)
40(12)
20(6)
5(1.5)
1(0.3)
0
0
DISTANCE, IN FEET (METERS)
475 (145)
EXPLANATION
REPOSITORY
CLAY CAP
–20(6)–
LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
WATER CONTENT AS A FRACTION OF PORE SPACE
0.5 - 0.1
0.1 - 0.15
0.5 - 0.6
0.6 - 0.8
0.8 - 1.0

Figure 42. Water content, flow lines, and lines of equal hydraulic head: Model 6, infiltration of 38 and 0.38 mm per year for silty sand and clay, respectively; and model 7, infiltration of 76 and 0.76 mm per year for silty sand and clay, respectively.

ed results for model 7 in figures 41 and 42 are for inflow rates of 76 and 0.76 mm/yr for silty sand and clay, respectively.

The effects of decreasing the thickness of the unsaturated zone are shown in figures 43 through 46. Boundary conditions for models 6 and 8 in figures 43 and 44 are the same as the boundary conditions for model 6 in figures 41 and 42; boundary conditions for models 9 and 7 in figures 45 and 46 are the same as the boundary conditions for model 7 in figures 41 and 42.

The most significant hydrologic feature of figures 40 through 46 is the flow barrier posed by the clay cover. The sand in the trench has no apparent effect on the convergence of flow lines beneath the clay. Flow lines converge in shorter vertical distances where the water table is deeper. Lesser water content, beneath the clay,

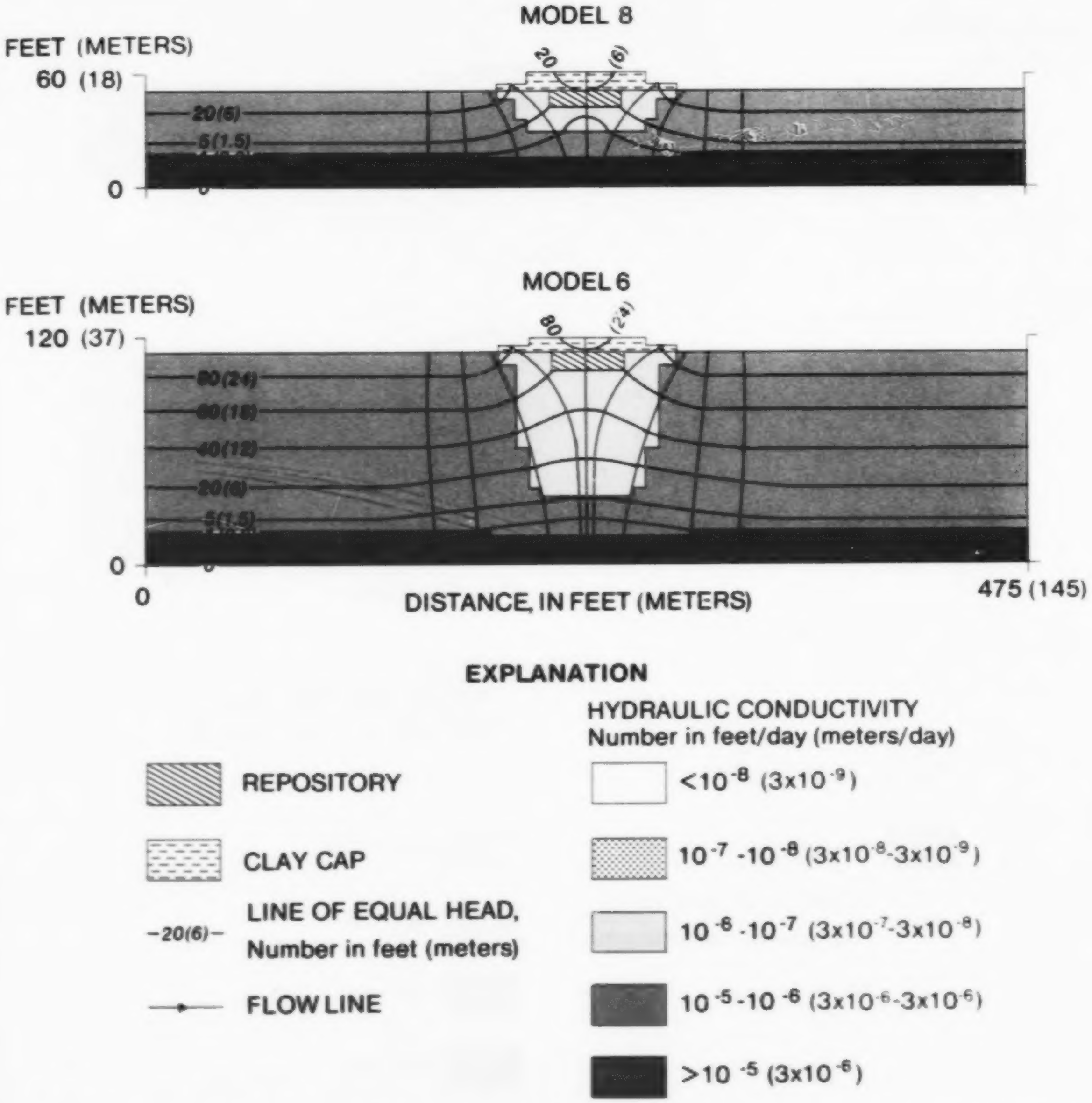
MODEL 8
FEET (METERS)
60 (18)
20
(6)
20(6)
5(1.5)
0
MODEL 6
FEET (METERS)
120 (37)
80
(24)
80(24)
60(18)
40(12)
20(6)
5(1.5)
0
0
DISTANCE, IN FEET (METERS)
475 (145)
EXPLANATION
HYDRAULIC CONDUCTIVITY
Number in feet/day (meters/day)
REPOSITORY
$<10^{-8}$ $(3x10^{-9})$
CLAY CAP
10^{-7} -10^{-8} $(3x10^{-8}$-$3x10^{-9})$
-20(6)-
LINE OF EQUAL HEAD, Number in feet (meters)
10^{-6} -10^{-7} $(3x10^{-7}$-$3x10^{-8})$
FLOW LINE
10^{-5} -10^{-6} $(3x10^{-6}$-$3x10^{-6})$
$>10^{-5}$ $(3x10^{-6})$

Figure 43. Unsaturated hydraulic conductivity, flow lines, and lines of equal hydraulic head for infiltration of 76 and 0.76 mm per year for silty sand and clay, respectively: Model 8, unsaturated zone thickness equals 15 m; and model 6, unsaturated zone thickness equals 33.5 m.

extends to a greater depth where the water table is deeper.

Factors Affecting Model Simulations

The hydrologic environment just below the land surface is dynamic and usually has considerable time variations. Steady-state models that attempt to represent this environment, such as those discussed in this paper, need to be interpreted with caution and checked by nonsteady-state modeling.

The design of shallow-land burial trenches that depend on clay covers to divert water laterally (such as those depicted in figs. 40–46) needs to address the problem of cover integrity. Covers at or near the land surface can be damaged by shrinking and swelling, root penetration, burrowing by fauna, and other factors.

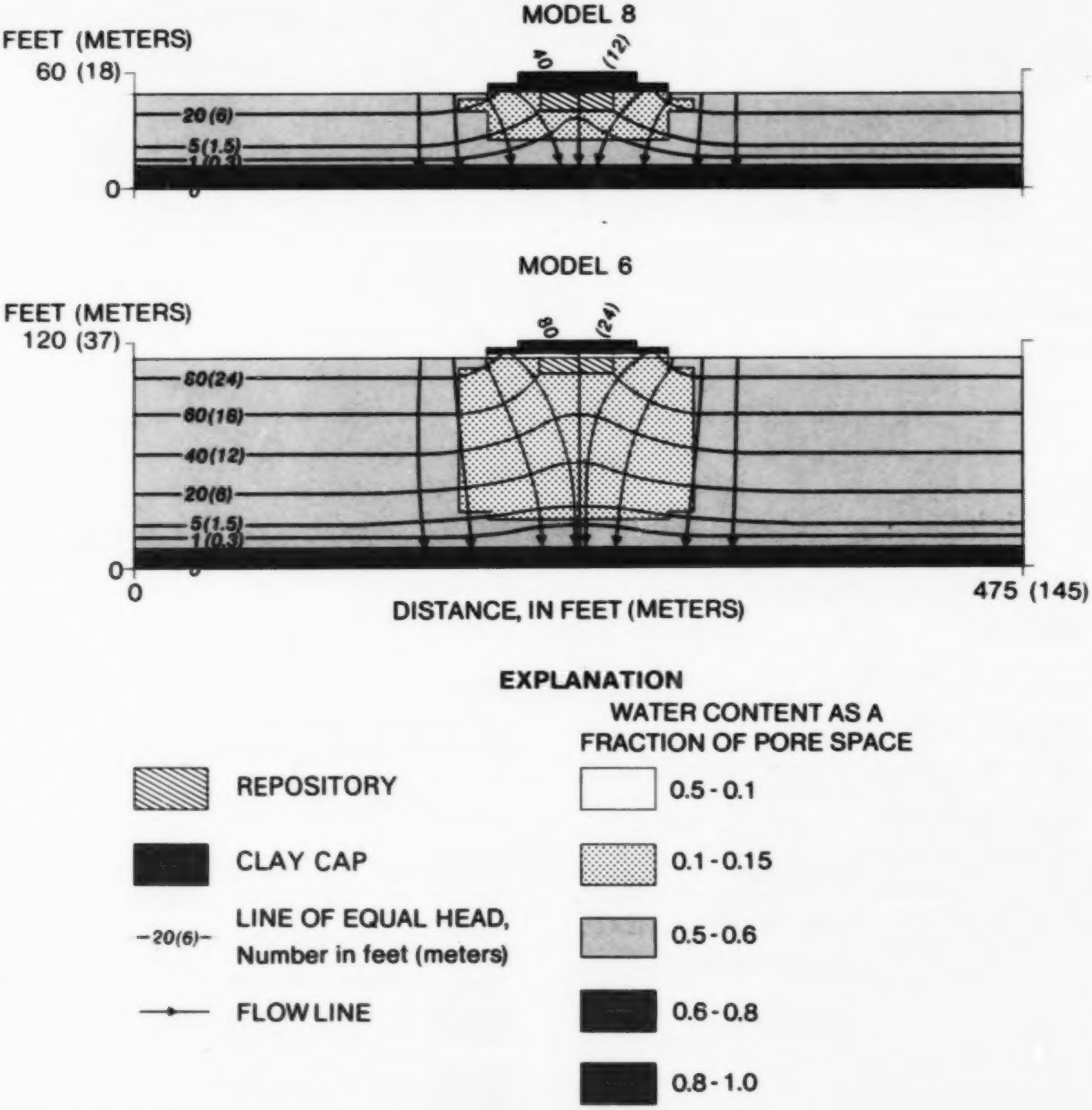
MODEL 8
FEET (METERS)
60 (18)
40
(12)
20(6)
5(1.5)
1(0.3)
0
0
MODEL 6
FEET (METERS)
120 (37)
80
(24)
80(24)
60(18)
40(12)
20(6)
5(1.5)
1(0.3)
0
0
0
475 (145)
DISTANCE, IN FEET (METERS)
EXPLANATION
REPOSITORY
CLAY CAP
-20(6)-
LINE OF EQUAL HEAD, Number in feet (meters)
FLOWLINE
WATER CONTENT AS A FRACTION OF PORE SPACE
0.5 - 0.1
0.1 - 0.15
0.5 - 0.6
0.6 - 0.8
0.8 - 1.0

Figure 44. Water content, flow lines, and lines of equal hydraulic head for infiltration of 38 and 0.38 mm per year for silty sand and clay, respectively: Model 8, unsaturated-zone thickness equals 15 m; and model 6, unsaturated-zone thickness equals 33.5 m.

Conclusions

The physical geometries and boundary conditions discussed in this paper indicate some of the factors involved in capillary barriers. Effectiveness of capillary barriers depends on the native medium, the implaced medium, and the moisture tension at the barrier location. The implaced medium needs to be tailored to the native medium and its water content. For example, if moisture content is too great in a native clay for fine sand to be a suitable barrier, then a coarser fill needs to be used.

Selection of the barrier material, then, depends on knowledge of the lithology, both vertically and laterally, and of the water content at the repository site. Also, it is necessary to know the unsaturated properties of available fill materials.

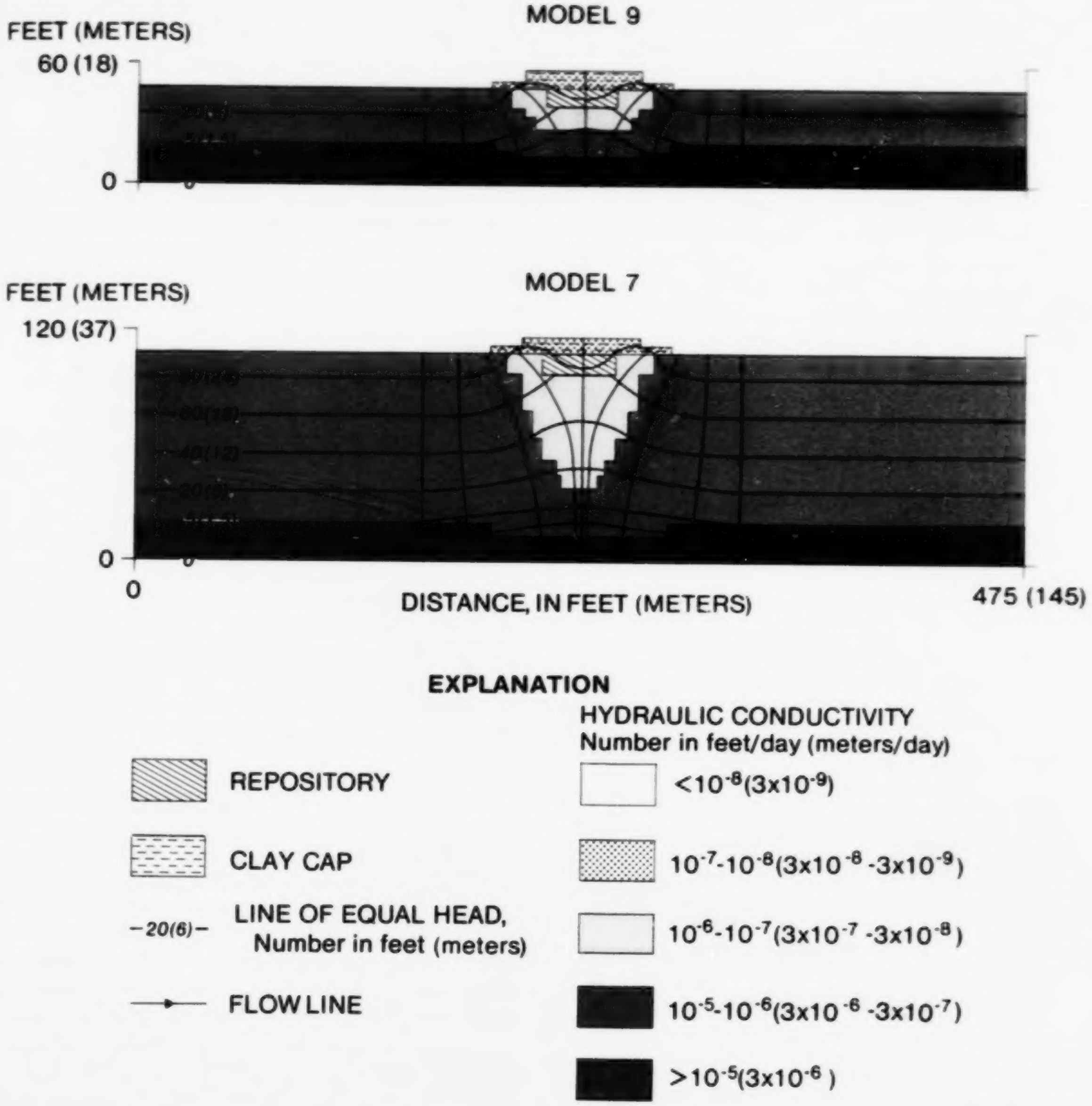
MODEL 9
FEET (METERS)
60 (18)
0
MODEL 7
FEET (METERS)
120 (37)
60(18)
40(12)
20(6)
0
0
DISTANCE, IN FEET (METERS)
475 (145)
EXPLANATION
REPOSITORY
CLAY CAP
-20(6)- LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
HYDRAULIC CONDUCTIVITY
Number in feet/day (meters/day)
<10-8(3x10-9)
10-7-10-8(3x10-8-3x10-9)
10-6-10-7(3x10-7-3x10-8)
10-5-10-6(3x10-6-3x10-7)
>10-5(3x10-6)

Figure 45. Unsaturated hydraulic conductivity, flow lines, and lines of equal hydraulic head for infiltration of 76 and 0.76 mm per year for silty sand and clay, respectively: Model 9, unsaturated-zone thickness equals 15 m; and model 7, unsaturated-zone thickness equals 33.5 m.

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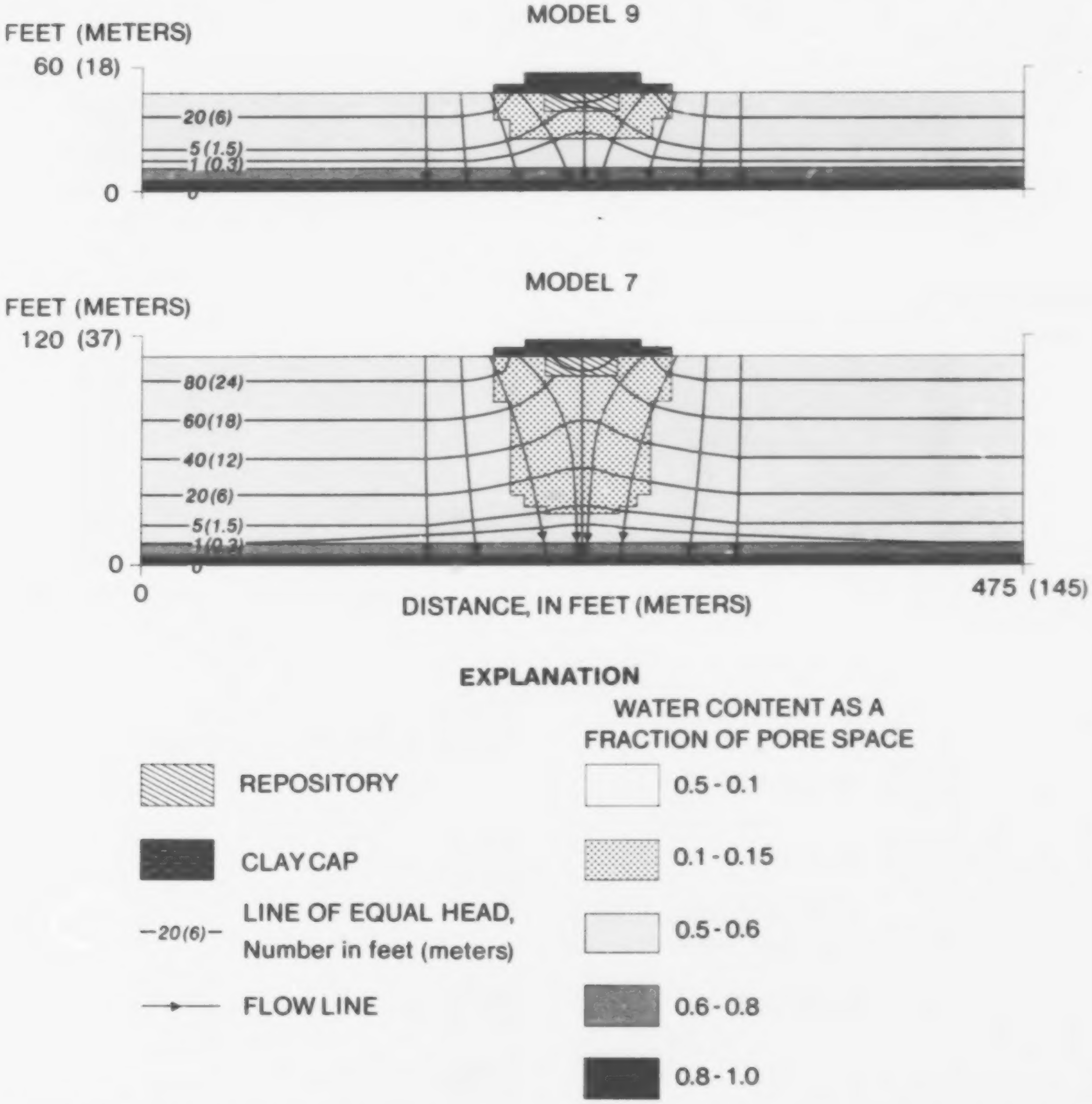
MODEL 9
FEET (METERS)
60 (18)
20(6)
5(1.5)
1(0.3)
0
0
MODEL 7
FEET (METERS)
120 (37)
80(24)
60(18)
40(12)
20(6)
5(1.5)
1(0.3)
0
0
0
475 (145)
DISTANCE, IN FEET (METERS)
EXPLANATION
WATER CONTENT AS A FRACTION OF PORE SPACE
REPOSITORY
CLAY CAP
–20(6)– LINE OF EQUAL HEAD, Number in feet (meters)
FLOW LINE
0.5 - 0.1
0.1 - 0.15
0.5 - 0.6
0.6 - 0.8
0.8 - 1.0

Figure 46. Water content, flow lines, and lines of equal hydraulic head for infiltration of 76 and 0.76 mm per year for silty sand and clay, respectively: Model 9, unsaturated-zone thickness equals 15 m; and model 7, unsaturated-zone thickness equals 33.5 m. The most significant hydrologic feature of figures 40 through 46 is the flow barrier posed by the clay cover.

Trench–Cover Systems for Manipulating Water Balance on Low-Level Radioactive-Waste Repository Sites

By Thomas E. Hakonson, Leonard J. Lane, John W. Nyhan, Fairley J. Barnes, *and* Gerald L. DePoorter

The effectiveness of a repository site consisting of burial trenches in isolating low-level radioactive waste is markedly affected by the characteristics of precipitation falling on the site. Precipitation in the form of rain or snow can cause erosion of burial-trench covers and percolation of water into and through the burial trenches. Intrusion of plant roots and burrowing animals into the burial trenches also are affected by water in the soil via complex relations between the physical, biological, and chemical components of the system.

Predicting the effectiveness of a repository site in limiting transport of contaminants requires a good working knowledge of the interactions of water, or the water balance, on the site. Of equal importance is the fact that the ability to accurately predict water balance can be used to optimize remedial procedures for correcting water-related problems such as excessive runoff and the accompanying erosion and seepage through the burial trenches. Obviously, that knowledge also can be used to design new repository sites that improve chances of meeting site-effectiveness objectives.

This paper discusses the results of research at the Los Alamos National Laboratory to measure, model, and manipulate components of the water balance at low-level radioactive-waste repository sites. These results are based on research at several locations, including the Los Alamos Experimental Engineered Test Facility (DePoorter, 1981) and the Nevada Test Site (Simanton and others, 1986), and involve a large number of collaborators including the U.S. Department of Agriculture, Agricultural Research Service; the University of California at Los Angeles; the Nevada Applied Ecology Group; and the Environmental Science Group at Los Alamos National Laboratory.

Water Balance Components

Flow components of the water balance of major importance affecting site effectiveness are depicted in the schematic diagram of a shallow burial trench in figure 47. Precipitation that falls on the land surface is partitioned into runoff, infiltration, percolation, storage in the soil, and evapotranspiration. Design features that can be modified to affect the water balance include the type and thickness of trench-cover soil, the slope and slope length of the trench-cover surface, the land-surface management practice (use of mulches, and so forth), and the density, rooting characteristics, and transpiration potential of the plant cover. Ideally, we would like to direct as much of the incoming precipitation as possible to the evapotranspiration component in order to minimize problems with runoff, infiltration, and percolation. Although runoff by itself does not contribute to repository-site failure, the erosion associated with it needs to be within specified tolerances to ensure that the trench covers remain intact during the mandated duration of the site. Infiltration and deep percolation can be controlled by maximizing evapotranspiration and by using trench-cover soils that store and retard water movement downward through the soil.

It is important to note that the components of water balance are so interdependent that modification of one of those components can produce large changes in one or more of the others. For example, in semiarid and arid areas, a small change in evapotranspiration, which often accounts for greater than 75 percent of the incident precipitation, can change infiltration, which is characteristically small in semiarid and arid areas, by as much as an order of magnitude. Similarly, changes in runoff can increase or decrease the infiltration of water into the trench covers. Although it is true that we would like to predict the effect of specific design modifications on all components of water balance, it also is true that many of our techniques for measuring water-balance components are subject to substantial errors. A section at the end of this paper discusses some innovative approaches for measuring evapotranspiration, a dominant component of water balance, and factors affecting it.

The relevance of understanding the relation of the water balance to repository-site design and remedial action are discussed in detail in Hakonson and others (1982), Nyhan and Lane (1982), Lane (1984), Hakonson and others (1986), and Nyhan and Lane (1986a). Overall,

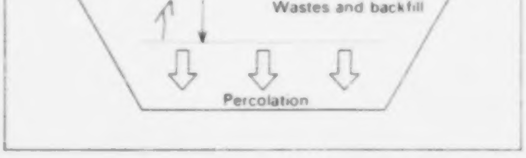

Figure 47. Flow components that can affect the integrity of low-level radioactive-waste repository sites. It is important to note that the components of the water balance are so interdependent that modification of one of those components can produce large changes in one or more of the others.

a water-balance approach to design and corrective measures at low-level radioactive-waste repository sites offers the following advantages:

1. It accounts for most of the climatological, hydrological, and biological factors that affect site integrity.
2. Water-balance models can be used to screen various designs and design modifications for effect on runoff and erosion, infiltration, percolation, and so forth.
3. It can be used to estimate upper boundary conditions for subsurface-water flow important in estimating leachate production and contaminant transport by ground water.

Trench–Cover Technology for Manipulating the Water Balance

The Environmental Science Group at Los Alamos National Laboratory began studies of water balance on trench covers in 1981 as part of the U.S. Department of Energy's National Low-Level Radioactive-Waste Management Program. Those studies were conducted in a 9-ha study site at the Laboratory designated as the Los Alamos Experimental Engineered Test Facility (DePoorter, 1981), and relied on rainfall-simulator technology (Renard, 1986) to evaluate the hydrologic response of a variety of trench-cover designs in a semiarid environment. Large caissons (3 m diameter by 6 m deep) also were used to investigate subsurface processes including the affect of capillary barriers on percolation. Results of that work have been published in about 140 journal papers, symposia proceedings, and government and laboratory reports.

In 1984, the results from several previous studies were used to design and emplace a trench-cover demonstration called the Low-level Integrated Systems Test Project (Abeele, 1986) (fig. 48). The purpose of the demonstration was to monitor and compare the water balance on a conventional trench-cover design (fig. 49) with that on an improved design (fig. 50). The latter design incorporated our best available knowledge on methods to control erosion (Nyhan and Lane, 1986a,b); percolation (Lane, 1984; Hakonson, 1986); and biological intrusion (Hakonson, 1986).

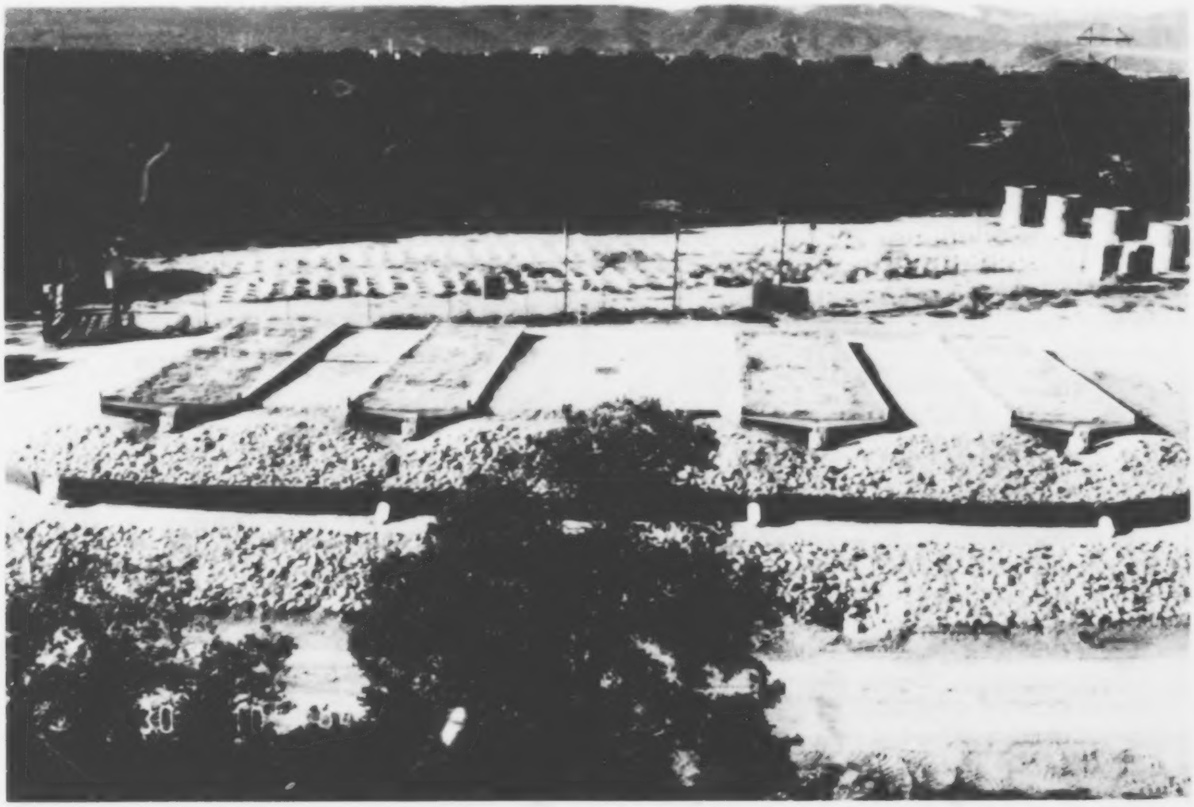

Figure 48. Four field plots of trench-cover demonstration used in the Low-level Integrated Systems Test Project at the Los Alamos National Laboratory, N.M. The purpose of the demonstration was to compare the water balance on a conventional trench-cover design with that on an improved trench-cover design.

The demonstration plots were designed and instrumented so that a complete accounting of precipitation falling on the plots could be made. The plots, which were about 3 m wide by 10 m long, were constructed and instrumented (figs. 49 and 50) to provide measures of runoff and erosion, soil-water storage, and seepage, as measured by leachate production at the various drains (Abeele, 1986). No artificial precipitation was added to the plots during the course of the study.

The technology for controlling erosion on the plots consisted of applying a 60- to 70-percent cover of gravel with a thickness of about 2 cm and a slope of 0.5 percent and planting a cover of blue gramma (*Bouteloua gracilis*) and western wheat grass (*Agropyron smithii*). This erosion-control design was developed from results of rainfall-simulator studies at the Los Alamos National Laboratory (Nyhan and others, 1984; Nyhan and Lane, 1986b) and at the Nevada Test Site where the affect of the natural erosion pavement, which covers the soil surface in the Northern Mojave Desert, on the water balance has been extensively studied (Hakonson and others, 1986; Simanton and others, 1986; Romney and others, 1986).

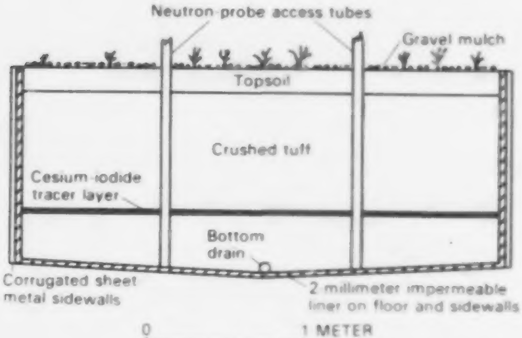
Neutron probe access tubes
Gravel mulch
Topsoil
Crushed tuff
Cesium iodide tracer layer
Bottom drain
Corrugated sheet metal sidewalls
2-millimeter impermeable liner on floor and sidewalls
0
1 METER

Figure 49. Conventional trench-cover design on the integrated systems test plots at the Los Alamos National Laboratory, N.M. Compare the features with those of the improved trench-cover design in figure 50.

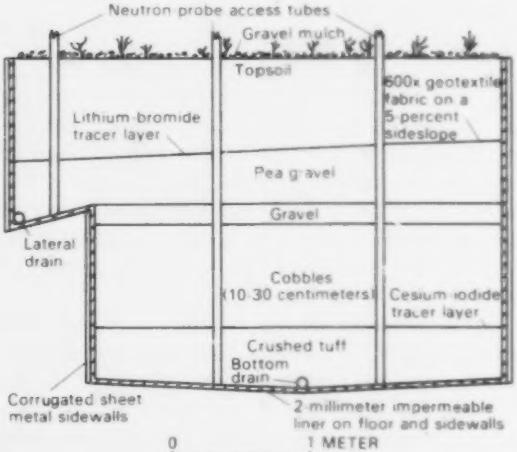
Neutron probe access tubes
Gravel mulch
Topsoil
600x geotextile fabric on a 5-percent sideslope
Lithium-bromide tracer layer
Pea gravel
Gravel
Lateral drain
Cobbles (10-30 centimeters)
Cesium iodide tracer layer
Crushed tuff
Bottom drain
Corrugated sheet metal sidewalls
2-millimeter impermeable liner on floor and sidewalls
0
1 METER

Figure 50. Improved trench-cover design on the integrated systems test plots at the Los Alamos National Laboratory, N.M. After 3 years of measuring, erosion, infiltration, percolation, and biointrusion were decreased or eliminated using this design instead of the conventional design (fig. 49).

Percolation or seepage control is provided by the pea-gravel part of the layered-rock component (fig. 50) of the trench cover; the pea gravel functions as a capillary barrier to downward water flow (Abeele, 1986; Hakonson, 1986). The difference in saturated hydraulic conductivity of the pea gravel and the overlying topsoil causes downward water flow to be impeded at the interface of these materials. A 5-percent lateral slope of the interface between the topsoil and gravel allows gravity to convert the downward-flow component to a lateral-flow component. Lateral flows then can be diverted away from the trench to a lateral drain, precluding the movement of water through the cover into the trench. The integrity of the topsoil/pea-gravel interface is maintained with a geotextile fabric (fig. 50). Failure of the capillary barrier can occur when the topsoil at the interface becomes saturated with water. The objective, then, is to keep topsoil overlying the capillary barrier as dry as possible by maximizing evapotranspiration losses.

The cobble layer underlying the gravel layer prevents plant root penetration and animal intrusion; it was designed based on the results of several tests at the Experimental Engineered Test Facility and at several low-level radioactive-waste burial trenches at the Los Alamos National Laboratory (Hakonson, 1986). The cobble layer prevents and minimizes plant-root penetration because the spaces between the cobbles are almost free of soil and water. As long as there is a limited source of nutrients and water in the cobble layer, plant-root penetration into this layer will be minimized. The cobble layer also prevents most burrowing animals from digging through the layer simply because the cobbles are too heavy to move.

Results and Discussion

Three years of data have been collected on the Low-Level Integrated Systems Test Plots. During that time, we have demonstrated that with the improved trench-cover design we can eliminate or decrease erosion, infiltration, percolation, and biointrusion compared to that measured on the conventional trench-cover design. From May 1984 through March 1987, a total of 2,100 mm of precipitation fell on the plots which, on an annual basis, greatly exceeds the average annual precipitation of about 460 mm at the Los Alamos National Laboratory. Snowfall during the winter and spring of 1984–85 was 250 percent greater than the average snowfall of 1,300 mm at the Los Alamos National Laboratory.

Table 12. Drainage from integrated systems test plots at the Los Alamos National Laboratory, N.M., May 1984 through April 1987

Trench-cover system	Date	Drainage (liters)	Percentage of total precipitation on test plots to date drainage stopped
Conventional design: (see fig. 49)	April–May 1985	161	[1]0.66
	Dec. 1986–April 1987	3,047	[2]5.0
Total		3,208	5.02
Improved design: (see fig. 50)			
Lateral drains above capillary barrier.	April–May 1985	335	[3]1.2
Bottom drains below capillary barrier.	April–May 1985	0	0
Lateral drains above capillary barrier.	Dec. 1986–April 1987	500	[4]0.69
Bottom drains below capillary barrier.	Dec. 1986–April 1987	769	1.1
Total:			
Lateral drains		835	1.2
Bottom drains		769	1.1

[1] Total precipitation on plots with conventional trench-cover design when drainage stopped was 24,283 liters.

[2] Total precipitation on plots with conventional trench-cover design when drainage stopped was 61,247 liters.

[3] Total precipitation on plots with improved trench-cover design when drainage stopped was 27,903 liters.

[4] Total precipitation on plots with improved trench-cover design when drainage stopped was 72,260 liters.

During the winter of 1986–87, a total of 3,350 mm of snow fell on the plots; this snowfall exceeded the record annual snowfall of 3,120 mm at the Los Alamos National Laboratory.

Leachate production from the various drains are summarized in table 12. During the 3 years, drainage from plots with the conventional trench-cover design occurred on two occasions, both of which were after a large snowfall. On the first occasion (April-May 1985), 161 L of leachate was produced that was about 0.66 percent of the precipitation that had fallen on these plots. The second period of drainage (December 1986–April 1987), which was after a snowfall of 1,370 mm, produced 3,047 L of leachate that was about 5 percent of the total precipitation on the plots to that time.

The improved trench-cover design was considerably better than the conventional trench-cover design in controlling drainage during the two periods. During the first period (April-May 1985), there was no drainage from the bottom drains of the improved trench-cover designs. However, a lateral drainage totaling 335 L did occur, and this amount represents about 1.2 percent of the total precipitation. During the second period (December 1986–April 1987), drainage occurred from the lateral and bottom drains. The lateral drainage totaled 500 L, which represents about 0.69 percent of the total precipitation, and the bottom drain totaled 769 L, which represents about 1.1 percent of the total precipitation that fell on the plots.

Altogether, about 1.2 percent of the precipitation falling on the plots with the improved trench-cover design from May 1984 through March 1987 was diverted laterally through the topsoil above the capillary barrier; this diversion decreased percolation to deeper zones in the trench-cover profile by more than one-half. The improved trench-cover design also decreased the bottom drainage, or leachate production, by a factor of 4 compared to the conventional trench-cover design (769 L versus 3,208 L, table 12).

The presence of the capillary barrier in the improved trench-cover design also strongly affected the moisture content of the topsoil and, therefore, the growth of the plant cover. After precipitation on the plots, the moisture content of the topsoil overlying the capillary barrier was about 5 percent (by volume) greater in plots with the improved trench-cover design (fig. 51) than that measured at a comparable depth in plots with the conventional trench-cover design (fig. 52). For example, during the winter of 1984–85, when infiltration from melting snowfall was being added to the plots, the volumetric moisture content of the topsoil at a depth of 60 cm in plots with the improved trench-cover design appears to be less than at a comparable depth in plots with the conventional trench-cover design. These differences likely are due to the retardation of downward water flow caused by the capillary barrier in plots with the improved design compared to the unimpeded downward flow in plots with the conventional design.

Because plant growth in semiarid and arid environments often is water limited, the enhanced availability of water in the topsoil over the capillary barrier should stimulate plant growth and leaf area with a corresponding increase in transpiration of water from the plant surfaces. Total biomass measurements for the two grass species seeded on the plots in August 1986 (table 13) indicate that the plots with the improved trench-cover design supported 2 to 3 times more biomass than those with the conventional trench-cover design. Furthermore, the biomass of grasses on plots with both trench-cover designs was enhanced compared with that measured on undisturbed soil owing to the use of the gravel mulch or the capillary barrier or both on the test plots. The net effect of the increased grass biomass on plots with the improved trench-cover design was that, when the plants were actively transpiring, the moisture content of the topsoil averaged 2 to 5 percent by volume less (as shown by data for June-September 1985 in figs. 51 and 52) than at equivalent depths on plots with the conventional trench-cover design. Consequently, the volume of water that could be stored in the topsoil above the capillary barrier was greater than that for an equivalent depth in the topsoil not underlain by a capillary barrier. This is especially apparent during the winter of 1985–86 (a dry winter), when the moisture content of the topsoil at the 60-cm depth on plots with the improved trench-cover design averaged about 14 percent compared to an average of about 22 percent at the 80-cm depth on plots with the conventional trench-cover design.

Penetration of vegetation roots through both trench-cover designs was evaluated by analyzing above-

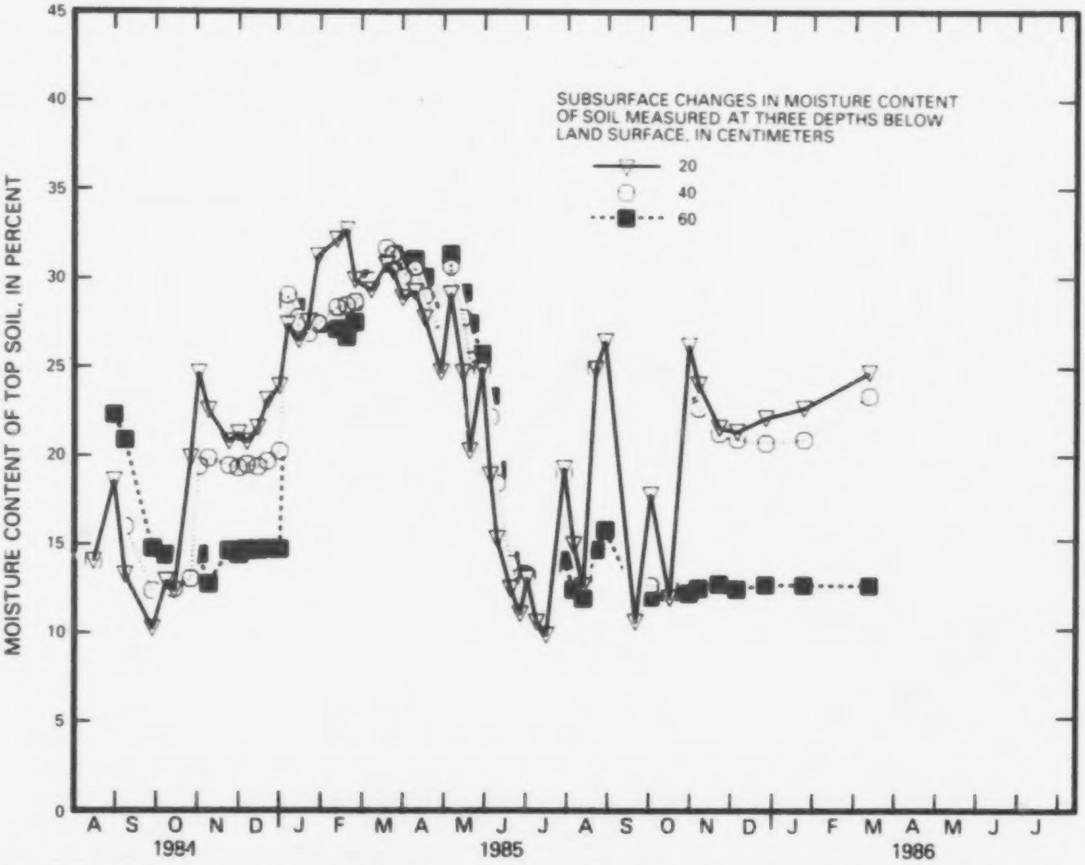

Figure 51. Moisture content of topsoil at various depths from the land surface in the integrated systems test plots with the improved trench-cover design at the Los Alamos National Laboratory, N.M., August 1984 through March 1986. The letters, J to D stand for the names of the months of the year. Compare with results of the conventional trench-cover design shown in figure 52.

ground plant samples for a cesium-iodide tracer that was placed near the bottom of each cover profile (figs. 49 and 50). Plant-root penetration through the conventional trench-cover design occurred within 2 years after seeding the plots, whereas the cobble layer in the improved design has, thus far (1987), prevented root access to the tracer for 3 years. Previous studies (Hakonson, 1986) demonstrated that the cobble biointrusion barrier decreased plant-root penetration by factors of 2 to 8 compared to the conventional trench-cover design.

In summary, simple concepts of water balance can be applied to the design and remediation of low-level radioactive-waste repository sites to control runoff and erosion, infiltration, percolation, and biological intrusion. We have determined that a thin covering of gravel (60–70 percent cover with a thickness of about 2 cm), a gentle slope (< 1 percent) and a dense (70 to 80 percent) cover of native grasses effectively eliminated runoff and erosion during a 3-year study despite the occurrence of several intense rainstorms. Likewise, the use of a combination

Table 13. Plant biomass on the trench covers of the integrated systems test plots at the Los Alamos National Laboratory, N.M., August 1986

Trench-cover design	Biomass[1] (grams per square meter)
Conventional (topsoil and crushed tuff with gravel mulch on land surface (fig. 49).	340–460
Improved (topsoil over pea-gravel capillary barrier over biointrusion barrier, cobbles, with gravel mulch on land surface (fig. 50).	850–1,245
Natural vegetation on undisturbed soil.	80–200

[1] Range based on 22 measurements per trench-cover design; plant composition on the plots with the conventional design was exclusively blue grama (*Bouteloua gracilis*), whereas it was a mixture of blue grama and western wheat grass (*Agropyron smithii*) on plots with the improved design.

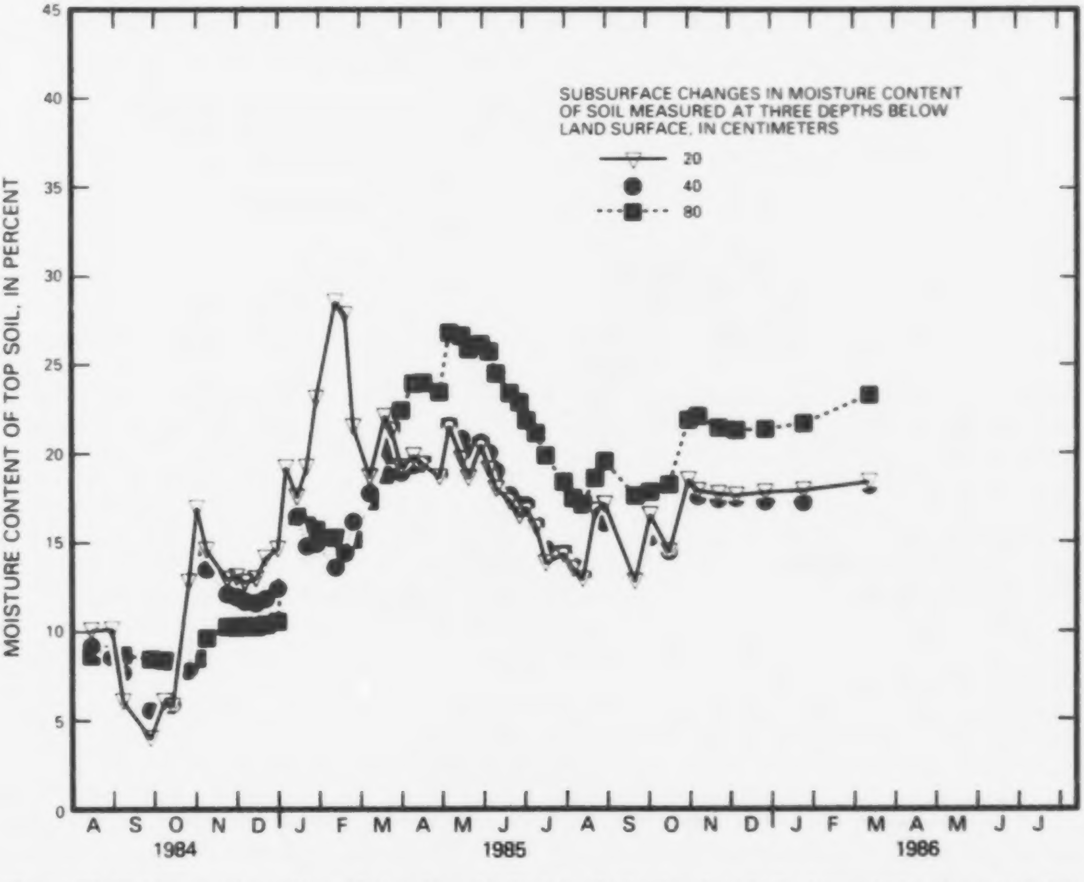

Figure 52. Moisture content of topsoil at various depths from the land surface in the integrated systems test plots with the conventional trench-cover design at the Los Alamos National Laboratory, N.M., August 1984 through March 1986. The letters, J to D, stand for the months of the year. Compare with results of the improved trench-cover design shown in figure 51.

biointrusion-capillary barrier decreased percolation by a factor of 4 and diverted a substantial proportion of the percolating water laterally, decreasing deep percolation by a factor of about 2. The cobble-layer component of the trench cover also completely prevented plant-root penetration through the trench cover into a simulated waste.

A secondary, and important, benefit of the biointrusion-capillary barrier is the effect it had on plant growth. The retention of moisture in the topsoil above the barrier resulted in an increase of a factor of 2 to 3 in plant biomass compared to the growth on plots with the conventional trench-cover design. Because leaf area is correlated with biomass for many species, transpiration also would be expected to be greater. Greater transpiration is evident on plots with the improved trench-cover design because of the lesser moisture content of the topsoil after periods of precipitation. Of course, the drier the soil is, the greater is its capacity to absorb incoming precipitation.

New Directions

A critical weakness in our understanding of and our ability to model the water balance is the lack of data and methods to measure evapotranspiration throughout large areas. In arid areas, a large fraction of annual precipitation may be lost to evapotranspiration. A major problem at low-level radioactive waste-repository sites may result from water that percolates below the root zone where it is free to interact with the buried waste and possibly move, along with solutes, outside the repository-site boundaries. Because plants have such a dominant effect on the water balance, revegetation with species that maximize water use may help resolve the problem of percolation to and through the buried waste. Unfortunately, data pertaining to evapotranspiration from plant canopies, as a function of species and season, that could be used in selecting an optimum cover generally are few.

Estimates of evapotranspiration from stands of vegetation by measuring profiles of water vapor, temperature, and wind above the canopy always have been difficult, especially without perturbing the profiles during the measuring. Recent developments in *LI*ght *D*etection *A*nd *R*anging (LIDAR) technology for remote monitoring of the concentration of atmosphere constituents, such as water vapor, have created an unprecedented opportunity for obtaining data pertaining to these processes by noninterfering means both at ground level and aloft. We are developing and applying specific LIDAR techniques for measuring evapotranspiration over a variety of native plant canopies using well-defined plant physiological conditions. Important links will be established between water flux and plant physiological conditions.

Soil and plant-root structure also greatly affect the water balance. We are exploring the use of an acoustic source, using a technique called cross-borehole acoustic tomography, to determine if we can measure structural features of plant roots noninvasively, in situ, and within several-meter interrogation ranges. We currently (1987) are developing an acoustic source capable of transmission of high frequency energy through soil and plant tissue, yielding a resolution between 1 mm and 1 cm. Computerized tomographic techniques, pioneered by the medical profession, will be used to examine kinematic and dynamic properties of the seismic-wave field to indicate soil structure.

Conclusions

Water-balance components are important in understanding and predicting the effectiveness of shallow burial trenches for storage of low-level radioactive wastes. On the basis of a synthesis of modeling results and onsite experiments at the Los Alamos National Laboratory and the Nevada Test Site, we designed, constructed, and instrumented a demonstration project called the Low-Level Integrated Systems Test. The improved trench-cover design incorporated erosion-control measures, a capillary barrier and lateral subsurface-flow diversion structure, and a plant-root/burrowing-animal intrusion barrier. The improved trench-cover design eliminated surface runoff and erosion and plant and animal intrusion during the 3-year study. The capillary barrier and lateral subsurface-flow diversion structure (fig. 50) decreased deep percolation into the simulated buried wastes by a factor of 4 (table 12) compared to that measured using a conventional trench-cover design.

Because deep percolation into the simulated wastes was not eliminated entirely during several wet years, we conclude there is a continuing need for monitoring leachate production at the test plots. Moreover, even though the improved trench-cover design decreased deep percolation, and thus leachate production, by a factor of 4, it did fail during two extremely wet winters. This indicates consideration of passive leachate-collection systems as a backup to improved trench-cover designs as described herein.

A critical weakness in our understanding and ability to model the water balance is the lack of data and methods to measure evapotranspiration throughout large areas. Recently developed technology, such as LIDAR and cross-borehole acoustic tomography, are proposed as noninvasive methods of measuring evapotranspiration rates and plant-root distribution, respectively.

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Hydrogeologic Information Needs for Low-Level Radioactive-Waste Disposal Sites

By Michael F. Weber

Introduction

The U.S. Nuclear Regulatory Commission's staff consider the ground-water pathway as one of the most important pathways for radionuclide transport from low-level radioactive-waste repository sites. This consideration is reflected in the Commission's regulations for low-level radioactive-waste repository sites in the U.S. Code of Federal Regulations, Title 10, Part 61, hereinafter referred to as 10 CFR Part 61 (U.S. Nuclear Regulatory Commission, 1982). These regulations require that applicants demonstrate compliance with performance objectives and other technical requirements based on hydrogeologic and other assessments. The regulations provide for a systems approach in isolating low-level radioactive waste by requiring a case-specific combination of site characteristics, facility design and operation, waste form and classification, site closure, and institutional controls. Although isolation need not be complete for hundreds of years, it must be sufficient to protect the public health and safety and the environment from potential effects associated with burial of low-level radioactive waste.

The types of hydrogeologic data and analyses that are needed to demonstrate compliance with the Commission's regulations for low-level radioactive-waste repository sites in 10 CFR Part 61 are summarized in this paper. Throughout this paper, the term "hydrogeologic information" is used to describe both hydrogeologic data and analyses based on the data. The reader is referred to other regulatory-guidance documents (Siefken and others, 1982; Pangburn, 1987; U.S. Nuclear Regulatory Commission, 1987a, b) for more detailed discussions of hydrogeologic-information needs.

The types of hydrogeologic information needed to demonstrate compliance with 10 CFR Part 61 are expected to vary on a case-specific basis. This variability is inherent in the systems approach incorporated in the regulations. For example, the types of hydrogeologic data necessary to demonstrate compliance of a low-level radioactive-waste repository site in a humid area might be considerably different than the data required for such a site in an arid area. The types of necessary hydrogeologic information also are expected to vary as a function of the design and operational characteristics of the disposal facility. Nevertheless, hydrogeologic information needed

Table 14. Compliance demonstrations relevant to hydrogeologic-information needs specified in the U.S. Code of Federal Regulations, Title 10, Part 61

Site suitability	Design	Monitoring	Environmental effects	Performance objectives
Demonstrate that:	Demonstrate that:	Demonstrate that:		Demonstrate:
1. The site is capable of being characterized, modeled, analyzed, and monitored [§61.50(a)(2)].	1. Site features are directed toward long-term isolation and avoid the need for active maintenance after site closure [§61.51(a)(1)].	1. The monitoring system is capable of providing early warning of radionuclide releases before they leave the site boundary during site construction and operation [§61.53(c)].	1. Assess the effects of waste burial on the environment [§51.45(b)(1)].	1. Protection of the general population from releases of radioactivity (§61.41).
2. The exploitation of known natural resources will not result in failure of the performance objectives [§61.50(a)(4)].	2. Covers minimize infiltration, direct percolating water away from buried waste, and resist degradation by surface geologic processes and biotic activity [§61.51(a)(6)].	2. The monitoring system is capable of providing early warning of radioactive releases before they leave the site boundary after site closure [§61.53(d)].	2. Identify adverse environmental effects that cannot be avoided and alternatives to the proposed action [§51.45(b)(2 and 3)].	2. Protection of individuals from inadvertent intrusion (§61.42).
3. The site provides sufficient depth to the water table to prevent ground-water intrusion into the waste [§61.50(a)(7)].			3. Analyze the balance between environmental effects and environmental, economic, technical, and other benefits [§51.45(c)].	3. Protection of individuals during operations (§61.43).
4. The hydrogeologic unit used for waste burial does not discharge ground water to the land surface within the site [§61.50(a)(8)].				4. Stability of the disposal site after closure (§61.44)

to demonstrate compliance with 10 CFR Part 61 can be categorized into several classes: site suitability, design, monitoring, environmental effects, and performance objectives (table 14).

Overall, an applicant must submit sufficient hydrogeologic information to demonstrate compliance with the performance objectives in Subpart C of 10 CFR Part 61. The Commission has provided more detailed technical requirements in Subpart D of 10 CFR Part 61 pertaining to site suitability, design, operations and closure, monitoring, waste classification and characteristics, and institutional requirements. The Commission's staff expects that hydrogeologic information will be necessary to demonstrate compliance with the site suitability (§61.50), design (§61.51), and monitoring requirements (§61.53). These minimum technical requirements help assure that the total system will meet the performance objectives. Hydrogeologic information submitted to demonstrate compliance with one of these requirements also may support compliance demonstrations for the other requirements, as well as for the performance objectives (§61.40–44) and environmental requirements (§61.10 and Subpart A of 10 CFR Part 61). Potential cross-referencing of hydrogeologic information needed for licensing low-level radioactive-waste disposal facilities is listed in table 15. After summarizing hydrogeologic-information needs for the technical requirements (§61.50, 51, and 53), this paper describes hydrogeologic information needed to demonstrate compliance with the performance objectives and requirements for environmental-impact assessments.

Site Suitability

The majority of the site-suitability requirements in 10 CFR Part 61.50 identify adverse geologic, hydrologic, and demographic site characteristics that must not be present at low-level radioactive-waste repository sites. These requirements are intended to function collectively with other requirements in Part 61 to help assure isolation of the waste for long periods. Site-suitability requirements have been emphasized in 10 CFR Part 61 because of the long-term importance of site characteristics in isolating low-level radioactive waste. Hydrogeologic information specifically is needed to demonstrate compliance with the following site-suitability requirements: capability of the site to be characterized, modeled, analyzed, and monitored [§61.50(a)(2)]; natural resources

Table 15. Potential cross-referencing of hydrogeologic information needed to demonstrate compliance with the U.S. Code of Federal Regulations, Title 10, Part 61

[For explanation of numbers, 1 to 4, see table 14]

Information	Site suitability				Design		Monitoring		Environmental effects			Performance objectives			
	1	2	3	4	1	2	1	2	1	2	3	1	2	3	4
Hydraulic head	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Moisture content			X	X	X	X	X	X	X	X	X	X	X	X	X
Hydraulic conductivity	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Unsaturated properties	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Unit geometry	X		X	X	X	X	X	X	X	X	X	X	X	X	X
Boundary conditions	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X
Water chemistry	X	X	X		X	X	X	X	X	X	X	X	X	X	X
Attenuation	X		X				X	X	X	X	X	X	X	X	
Source term			X		X	X	X	X	X	X	X	X	X	X	X
Induced processes	X		X	X	X	X	X	X	X	X	X	X	X		X
Natural processes	X	X	X	X	X	X	X	X	X	X	X	X	X		X
Supporting information	X	X	X	X	X	X	X	X	X	X	X	X	X	X	X

[§61.50(a)(4)]; depth to the water table [§61.50(a)(7)]; and hydrogeologic-unit discharge [§61.50(a)(8)].

Hydrogeologic data also may be necessary to demonstrate compliance with site-suitability requirements, such as free-draining surface water [§61.50(a)(5)], tectonic stability [§61.50(a)(9)], and environmental masking [§61.50(a)(11)].

Hydrogeologic information necessary to demonstrate compliance with the first requirement listed above (capability of the site to be characterized, modeled, analyzed, and monitored) will be determined on the basis of relative importance of the ground-water transport pathway. An applicant will need to demonstrate that site hydrogeology can be sufficiently defined and assessed to demonstrate compliance with the performance objectives. Therefore, compliance demonstrations relevant to 10 CFR Part 61.50(a)(2) must be linked to performance assessments. For example, a ground-water flow system dominated by discrete fracture flow or karst may not be suitable for a repository site because existing technology is not adequate to characterize, monitor, and model the system to demonstrate compliance with the performance objectives.

The types of information that may be necessary to demonstrate compliance with the first criterion include spatial and temporal, when necessary, distributions of hydraulic head, hydraulic conductivity, soil-moisture content, effective porosity, unit geometry, recharge and discharge relations, sorptive characteristics, soil and ground-water chemistry, rate and relative significance of natural hydrogeologic processes affecting repository-site suitability, and supporting information. Throughout this paper, supporting information means all information that supports the primary hydrogeologic information such as quality-assurance and quality-control information, testing specifications, data analysis, code verification and documentation, monitoring-system characteristics and protocols, and analytical methods and protocols.

The natural-resources criterion in §61.50(a)(4) applies to known natural resources including mineral, coal, and hydrocarbon deposits; geothermal energy resources; timber; and surface-water and ground-water resources. Applicants must demonstrate that exploitation of known natural resources will not result in the site not meeting the performance objectives in Subpart C of 10 CFR Part 61. Hydrogeologic information needed to demonstrate compliance with this criterion may include: water-quality and water-use information, cost assessments for developing water supplies, assessments of resource value, characteristics of alternative water resources (for example, quantity and quality), existing and projected water-use characteristics, institutional constraints on water-resource exploitation, assessments of the potential for inadvertent intrusion associated with resource exploitation, assessments of the effects of water-resource exploitation on repository-site performance, and supporting information.

The Commission's regulations for disposal of low-level radioactive waste require that applicants demonstrate that ground water will not saturate the waste after disposal. Hydrogeologic information needed to demonstrate compliance with the depth-to-water-table criterion in §61.50(a)(7) may include assessments of the spatial and temporal distribution of the following information:

hydraulic head, soil-moisture content, soil-moisture characteristic curves, hydraulic conductivity, boundary conditions (for example, infiltration and evapotranspiration), unit geometry, configuration of the burial trenches, backfill and waste-form specifications, assessments of the potential for ground-water intrusion, and supporting information.

The Commission's regulations provide for burial below the water table if the applicant can demonstrate that molecular diffusion is the dominant process of radionuclide transport and that diffusion will not violate the performance objectives in 10 CFR Part 61. Such demonstrations usually will require analyses based on several independent methods, including hydrodynamic, hydrochemical, and stable-isotopic and radioisotopic, to demonstrate that diffusion is the dominant process of radionuclide transport. In addition to the hydrogeologic information listed above, applicants may need to submit the following information to characterize the distribution of hydrogeologic site characteristics to support such demonstrations: effective porosity, hydraulic head, sorptive and attenuative characteristics, molecular-diffusion coefficients, hydrochemical information, stable-isotope concentrations, radioisotope concentrations, hydraulic conductivity, estimated concentration gradients, waste-form concentrations and leaching characteristics, and supporting information.

The hydrogeologic-unit-discharge criterion in §61.50(a)(8) stipulates that the hydrogeologic unit used for disposal must not discharge ground water to the land surface within the disposal site. Hydrogeologic information necessary to demonstrate compliance with this criterion may include the following information: location and characteristics of ground-water discharge areas, such as perennial and ephemeral streams, springs, seeps, swamps, marshes, and bogs, in proximity to the disposal site; geometry of hydrogeologic units used for burial; boundary conditions of affected units; temporal and spatial distribution of hydraulic head and conductivity; site boundary; assessments of the potential for ground-water discharge to the ground surface; and supporting information.

Design

The Commission's staff expects that hydrogeologic data also will be necessary to demonstrate compliance with the design requirements in 10 CFR Part 61.51, such as: (1) long-term isolation with minimal maintenance [§61.51(a)(1)]; (2) minimization of infiltration [§61.51(a)(4)]; and (3) minimization of water contact with waste [§61.51(a)(6)]. Necessary types of hydrogeologic data and analyses will be determined on a case-specific basis depending on location, design, operation, waste, and closure characteristics.

For example, an applicant may propose to minimize infiltration by constructing an earthen cover above the waste. In support of such a proposal, an applicant would need to demonstrate that the cover will be effective in minimizing infiltration to the extent practicable, in directing percolating water away from the buried waste, and in resisting degradation by surface geologic processes and biotic activity [§61.51(a)(4)]. Specific hydrogeologic information needed to support such a demonstration may include engineering specifications for the cover materials, hydraulic conductivity, soil-moisture content, soil-moisture characteristic curves, boundary conditions (for example, temporal and spatial variation of infiltration rates and quantity), durability of cover materials and their properties, and supporting information. The applicant also would need to demonstrate that the cover has been designed in conjunction with other facility components to provide for stability and long-term isolation with minimal need for continuing active maintenance after site closure [§61.51)(a)(1)].

Monitoring

In addition to compliance demonstrations for site suitability and design, applicants must demonstrate compliance with requirements for environmental-monitoring programs under §61.53. Applicants must demonstrate that the ground-water monitoring system, as a component of the environmental-monitoring program, is capable of providing early warning of radionuclide releases before they reach the site boundary [§61.53(c and d)]. Applicants should synthesize hydrogeologic information into conceptual and analytical models to develop sufficient understanding of the rates and directions of ground-water flow and contaminant transport to demonstrate that the ground-water monitoring system is capable of providing an early warning of radionuclide releases. Specific hydrogeologic-information needs for such demonstrations may include the following types of information: hydraulic head, hydrogeologic-unit geometry, hydraulic conductivity, effective porosity, storage characteristics, sorptive and attenuative characteristics, contaminant source terms, and supporting information.

Environmental Effects

Additional hydrogeologic data may be necessary to assess and mitigate potential environmental effects that are associated with low-level radioactive-waste repository sites. Applicants are required to assess potential environmental effects under the statutory framework created by the National Environmental Policy Act of 1969 as provided in 10 CFR Part 61 and 61.10. The types of hydrogeologic information necessary to assess and mitigate environmental effects will vary as a function of location, design, operational practices, waste type and form, and, ultimately, site-closure characteristics. The Commission's staff expects that hydrogeologic data submitted to demonstrate compliance with the technical requirements in 10 CFR Part 61 will provide a sufficient basis for assessing environmental effects.

Performance Objectives

The Commission's staff expects that applicants will use hydrogeologic information to help demonstrate compliance with the four performance objectives listed in Subpart C of 10 CFR Part 61. For most repository sites, hydrogeologic information used to support demonstrations of compliance with the technical requirements in Subpart D of Part 61 should provide a sufficient basis for developing performance assessments needed to demonstrate adequate: (1) protection of the general public from radioactive effluents (§61.41); (2) protection of inadvertent intruders (§61.42); (3) protection of individuals during operations (§61.43); and (4) long-term stability with minimal need for active maintenance (§61.44).

The types of hydrogeologic data and analyses necessary to demonstrate compliance with the performance objectives will vary on a case-specific basis depending on location, design, operational practices, waste type and form, and site-closure characteristics. Specific hydrogeologic information needs may include the following: hydraulic head, hydraulic conductivity, effective porosity, hydrogeologic-unit geometry, water chemistry, sorptive and attenuative characteristics, boundary conditions, soil-moisture content, soil-moisture characteristic curves, characteristics of known and likely future activities that may markedly affect the hydrogeologic system, characteristics of natural processes that may markedly affect the hydrogeologic system, source terms, and supporting information.

Applicants should integrate this information into a comprehensive systems model (or set of submodels) that adequately predicts repository-site performance and qualifies the uncertainties associated with the predictions. Model type, detail, and assumed conservatism must be determined by the applicant on the basis of specific modeling objectives and case-specific characteristics of the repository site. These models provide the foundation for performance assessments of low-level radioactive-waste repository sites, which are combined with expert judgment and model validation to ensure protection of the public health and safety, and the environment.

Summary

U.S. Nuclear Regulatory Commission regulations for disposal of low-level radioactive waste (10CFR Part 61) require hydrologic information to meet the performance objectives and other technical requirements that are based on hydrogeologic and other assessments. The regulations provide for a systems approach in waste isolation by requiring a case-specific combination of site characteristics, facility design and operation, waste form and classification, site closure, and institutional controls. Hydrogeologic information and analyses called for can be categorized into several classes: site suitability, design, monitoring, environmental effects, and performance objectives. Additional hydrogeologic data may be required to assess and mitigate potential environmental effects under the National Environmental Policy Act of 1969.

Specific hydrogeologic information needs may include: hydraulic head, hydraulic conductivity, effective porosity, hydrogeologic unit geometry, water chemistry, sorptive and attenuative characteristics, boundary conditions, soil-moisture content, soil-moisture characteristic curves, characteristics of known and likely future activities that may markedly affect the hydrogeologic system, characteristics of natural processes that may markedly affect the hydrogeologic system, source terms, and supporting information.

This information should be integrated into a comprehensive systems model (or set of models) that adequately predicts repository-site performance and qualifies the uncertainties associated with the predictions. These models provide the foundation for performance assessments of low-level radioactive-waste repository sites, and these models are combined with the expert judgment and model validation to ensure protection of the public health and safety and the environment.

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U.S. Department of Energy's Perspective on Disposal of Low-Level Radioactive Waste

By Scott T. Hinschberger

The U.S. Department of Energy's National Low-Level Radioactive-Waste Program consists of two separate but related entities—the Nuclear Energy Low-Level Waste Program (nondefense facilities) and the Defense Low-Level Waste Program. Part of the relation between these programs is the need for the Department to take into consideration events and trends occurring in the nondefense sector and apply them to concepts and practices used in the Defense Low-Level Waste Program.

The Department's primary role in the Nuclear Energy Low-Level Waste Program is to provide technical assistance to the States and compact regions. One of the technical assistance projects just completed involved the development of a conceptual-design report comparing six low-level radioactive-waste disposal concepts. The objective of this project was to examine low-level radioactive-waste disposal concepts that may be alternatives to traditional shallow-land burial. Because of the perceived problems associated with shallow-land burial, many of the States and compact regions are considering alternatives to shallow-land burial for new disposal facilities. Indeed, several have banned or restricted the use of shallow-land burial.

Six alternative disposal technologies were evaluated in the project:

1. Shallow-land disposal (SLD)
2. Intermediate-depth disposal (IDD)
3. Below-ground vaults (BGV)
4. Above-ground vaults (AGV)
5. Modular concrete canisters (MCCD)
6. Earth-mounded concrete bunkers (EMCB).

A standard design was used so that each technology could be evaluated under comparable and consistent conditions. All site and waste-form requirements of the U.S. Nuclear Regulatory Commission (1982) were assumed to be satisfied. Each site was assumed to be located in a characteristic area of the northeastern United States. The capacity of each conceptual design considered in the report was 2,492 m^3 of waste with an operation duration of 30 years. The average annual volume of waste to be isolated was 8,213 m^3.

The radioactive-waste source term used to assess the performance was based on information provided in three documents published by the U.S. Nuclear Regulatory Commission (Wild and others, 1981; U.S. Nuclear Regulatory Commission, 1982; and Oztunali and others, 1986). About 95 percent of the waste by volume was class A waste. The remaining 5 percent of the waste was class B and class C wastes. Class A waste was assumed to be placed in separate isolation units than those used for class B and class C wastes.

On the basis of these common descriptions, each technology was evaluated in the areas of worker industrial safety, worker radiological doses, radiological-performance assessment, costs, and schedule.

In evaluating the radiological-performance assessment, the following exposure possibilities were used:

1. Ground-water transport to an adjacent farm.
2. Intruder—explorer.
3. Intruder—construction.
4. Intruder—agriculture.

Exposures from each of the possibilities were modeled for 1,000 years after site closure. Three computer codes were used for the modeling. Onsite transport pathways were modeled using PATHRAE (Merrell and others, 1985). Ground-water flow in the unsaturated zone beneath the site was simulated using a modified version of UNSAT–11 (Fayer and others, 1986). Offsite transport pathways were modeled using PRESTO–CPG (Grant and others, 1984). Results of the evaluations are summarized in figure 53 and tables 16 through 19.

Results

Below-ground vault disposal causes the greatest radiological dose to workers (fig. 53); double the worker dose resulting from shallow-land disposal or intermediate-depth disposal, which causes the lowest dose. The radiological dose to workers caused by modular-concrete canister, above-ground vault, and earth-mounded concrete bunker disposal are only slightly less than for below-ground vault disposal and significantly greater then for shallow-land or intermediate-depth disposal.

As shown in table 16, shallow-land and intermediate-depth disposal cause the least worker injuries and risk of fatal accidents. Modular-concrete canister disposal causes the most worker injuries and risk of fatal accidents. Below-ground and above-ground vault disposal cause worker injuries and risk of fatal accidents that are significantly less than for modular-concrete canister disposal but are twice the worker injuries and risk of fatal accidents caused by shallow-land disposal.

As shown in table 17, peak annual doses for the adjacent-farmer scenario and the inadvertent-intruder scenario after the institutional control period are least for earth-mounded concrete bunker disposal and greatest by a factor of six or more for above-ground vault disposal. Peak annual doses calculated for below-ground, intermediate-depth, modular-concete canister, and shallow-land disposal are slightly higher than those for earth-mounded concrete bunkers but are lower by a factor of six or more than above ground-vault disposal.

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Cost estimates for the six conceptual isolation facilities are compared in table 18. Total costs were least for shallow-land disposal followed closely by intermediate-depth disposal. Total estimated costs of below-ground vault and modular-concrete canister disposal were more than 1.5 times and above-ground vaults almost twice that of shallow-land disposal. Total estimated costs were the highest for earth-mounded concrete bunker disposal, 2.2 times that of shallow-land disposal.

Qualitative assessment of the different disposal technologies for meeting U.S. Nuclear Regulatory Commission's (1982) regulations is given in table 19. In general, all six technologies are compatible with the U.S. Nuclear Regulatory Commission's (1982) regulations, with the possible exception of above-ground vaults. The analysis indicated that above-ground vaults would have difficulty meeting the long-term-stability and inadvertent-intruder requirements. In addition, the primary pathway for contamination migration would be through air and surface-water transport. In evaluating the below-ground technologies, radionuclides migrating away from the disposal site must be transported via ground water, thus providing extended periods for radioactive decay and the potential for adsorption within the buffer zone surrounding the disposal facility.

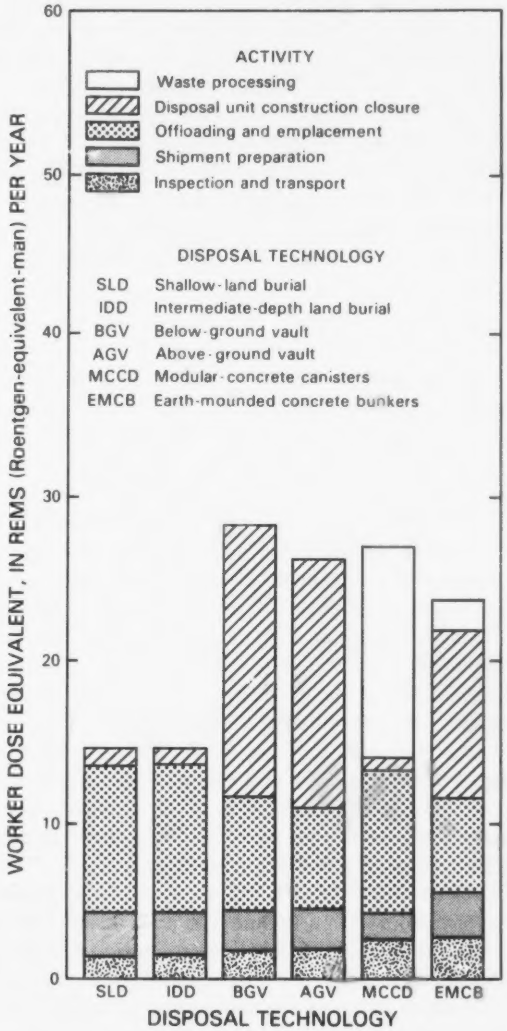

Figure 53. Worker doses caused by various waste-management activities. Radiological dose to workers is greatest for below-ground vault disposal, double the worker dose resulting from shallow-land disposal or intermediate-depth disposal, which cause the lowest dose.

Table 16. Lost-time worker injuries and fatal-accident risk during 30 years

Disposal technology	Lost-time worker injuries	Fatal-accident risk
Shallow-land disposal	9	0.05
Intermediate-depth disposal	10	.06
Below-ground vaults	20	.11
Above-ground vaults	19	.10
Modular-concrete canisters	24	.13

Table 17. Peak annual doses for scenarios after the institutional-control period

Disposal technology	Millirems per year	
	Adjacent-farmer scenario	Inadvertent-intrusion scenario
Shallow-land disposal	22	22
Intermediate-depth disposal	18	18
Below-ground vaults	16	16
Above-ground vaults	150	95
Modular-concrete canisters	19	19
Earth-mounded concrete bunkers	14	14

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Table 18. Comparison of cost estimates for six conceptual isolation facilities

[SLD, shallow-land disposal; IDD, intermediate-depth disposal; BGV, below-ground vaults; AGV, above-ground vaults; MCCD, modular-concrete canisters; EMCB, earth-mounded concrete bunkers]

Operating period	Costs (in millions of 1986 dollars)					
	SLD	IDD	BGV	AGV	MCCD	EMCB
Pre-operating period	21	22	25	26	30	36
Operating period	155	162	256	319	245	356
Closure period	6	6	7	6	8	10
Post-closure period	34	34	40	69	52	73
Total costs	216	224	328	420	335	475

Table 19. Qualitative assessment of disposal technologies for meeting regulatory standards

[SLD, shallow-land disposal; IDD, intermediate-depth disposal; BGV, below-ground vaults; AGV, above-ground vaults; MCCD, modular-concrete canisters; EMCB, earth-mounded concrete bunkers; +, meets requirements; +–, probably meets requirements; –, difficulty in meeting requirements]

Regulatory requirement	Disposal Technology					
	SLD	IDD	BGV	AGV	MCCD	EMCB
Protect the general population from releases of radionuclides.	+	+	+	+–	+	+
Protect individuals from inadvertent intrusion.	+	+	+	–	+	+
Protect workers during operation.	+	+	+–	+–	+–	+
Site stability after closure.	+	+	+	–	+	+–
Minimize contact of waste by water.	+	+	+	+–	+	+
Fill void spaces between waste packages.	+	+	+	+	+	+
Surface gamma-radiation doses restricted to acceptable levels.	+	+	+	+–	+	+
Segregate class A waste from other wastes.	+	+	+	+	+	+
Stability of class B and class C wastes.	+	+	+	+–	+	+

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Low-Level Radioactive-Waste Disposal Technologies—Current Concepts

By William F. Schwarz

There presently (1987) are a dozen or more new low-level radioactive-waste repository sites contemplated for development in the United States. Whatever the final number, eventually they are to replace the three present commercially operated sites near Barnwell, S.C.; near Richland, Wash.; and near Beatty, Nev., by 1993. Individual States, or groups of States called compact regions, are required under the Federal Low-Level Radioactive-Waste Policy Amendments Act of 1985 to become responsible for disposal of low-level radioactive waste generated in their jurisdiction, and most of them plan to develop new repository sites.

Although the geohydrology at these new repository sites throughout the United States is likely to be quite varied, all the sites will have to meet the U.S. Nuclear Regulatory Commission's site-suitability requirements for land isolation of low-level radioactive waste (U.S. Nuclear Regulatory Commission, 1982). Engineered barriers will not be credited for compensating for deficiencies in natural site suitability. The site itself must meet these requirements. However, engineered barriers can improve the performance of a low-level radioactive-waste disposal facility constructed on a suitable site, and almost all current (1987) low-level radioactive-waste disposal concepts do incorporate engineered barriers or other structural components. These engineered enhancements are intended to provide a degree of public safety and environmental protection substantially better than regulations require. However, the design and construction of most of the proposed engineered barriers presented here have not been tested. Furthermore, the implementation of an isolation technology must include consideration of the geohydrologic environment.

Land disposal of low-level radioactive waste is characterized by the U.S. Nuclear Regulatory Commission as either "near-surface" disposal, meaning burial on or within the upper 30 m of the Earth's surface, or "other than near-surface" disposal, meaning burial at depths greater than 30 m. Most current isolation technologies are of the near-surface type, and the low-level radioactive waste generally is placed no deeper than 17 m.

Disposal concepts usually are further characterized in terms of where the waste resides relative to the land surface or grade. In this paper, the disposal technologies are grouped into four such categories—above ground, below ground, above and below ground, and above or below ground. Eight disposal technologies are described:

1. Tumulus (above ground).
2. Improved shallow-land burial (below ground).
3. Augured holes (below ground).
4. Mined cavities (below ground).
5. Earth-mounded concrete bunkers (above and below ground).
6. Concrete vaults (above or below ground).
7. Modular structures/concrete canisters (above or below ground).
8. Store/Monitor/Retrieve units (above or below ground).

All these methods are near-surface technologies, except for the mined cavities. Augured holes are amenable to both deep- and shallow-waste disposal. Such holes have been augured to depths greater than 30 m, and deep augured holes are a credible disposal technology. Thus, in seven of the eight disposal methods described, waste resides on or within 17 m or less of the Earth's surface.

Tumulus

The tumulus or earth-mound disposal concept basically consists of a concrete pad constructed on grade, onto which waste containers are arranged several layers high with the sides of the stack sloped inward, stair-step fashion. The completed stack is covered with earthen material and then capped with a multilayered mound consisting of materials, such as clay, gravel, geotextile, and cobbles. The side slopes of the tumulus are made less steep by extending the multilayered mound farther out than the earth cover on all sides.

An example of the tumulus concept is the tumulus facility under construction at the Oak Ridge National Laboratory (Van Hoesen and Clapp, 1987). Its purpose is to demonstrate above-grade disposal of solid low-level radioactive waste. A reinforced-concrete pad measuring 32 m by 19.8 m has been constructed on grade. The pad is 20 cm thick in the center and 40 cm thick at the edges. Drainage collection is facilitated by a 1-percent slope to the pad and a 15-cm-high curb around its perimeter. Underlying the concrete pad is a complex pad foundation incorporating a 30-mm-thick plastic liner and sand layers. Any drainage from the pad or liner will be collected and analyzed. Waste will be placed into standard 1.2 m by 1.2 m by 1.8 m boxes, and the boxes will be placed into reinforced-concrete modules sized to accept them with 7.5 cm of clearance. The remaining void spaces will be filled with grout and the module lid sealed in place. The sealed modules then will be positioned two high on the pad with forklifts (fig. 54). When the pad is full, an earthen cover will be placed over the modules. The cover design has not been selected, but three designs are being evaluated (fig. 55).

Improved Shallow-Land Disposal

As originally practiced, shallow-land burial of low-level radioactive waste basically was an adaptation of techniques and practices used at landfills. Typically,

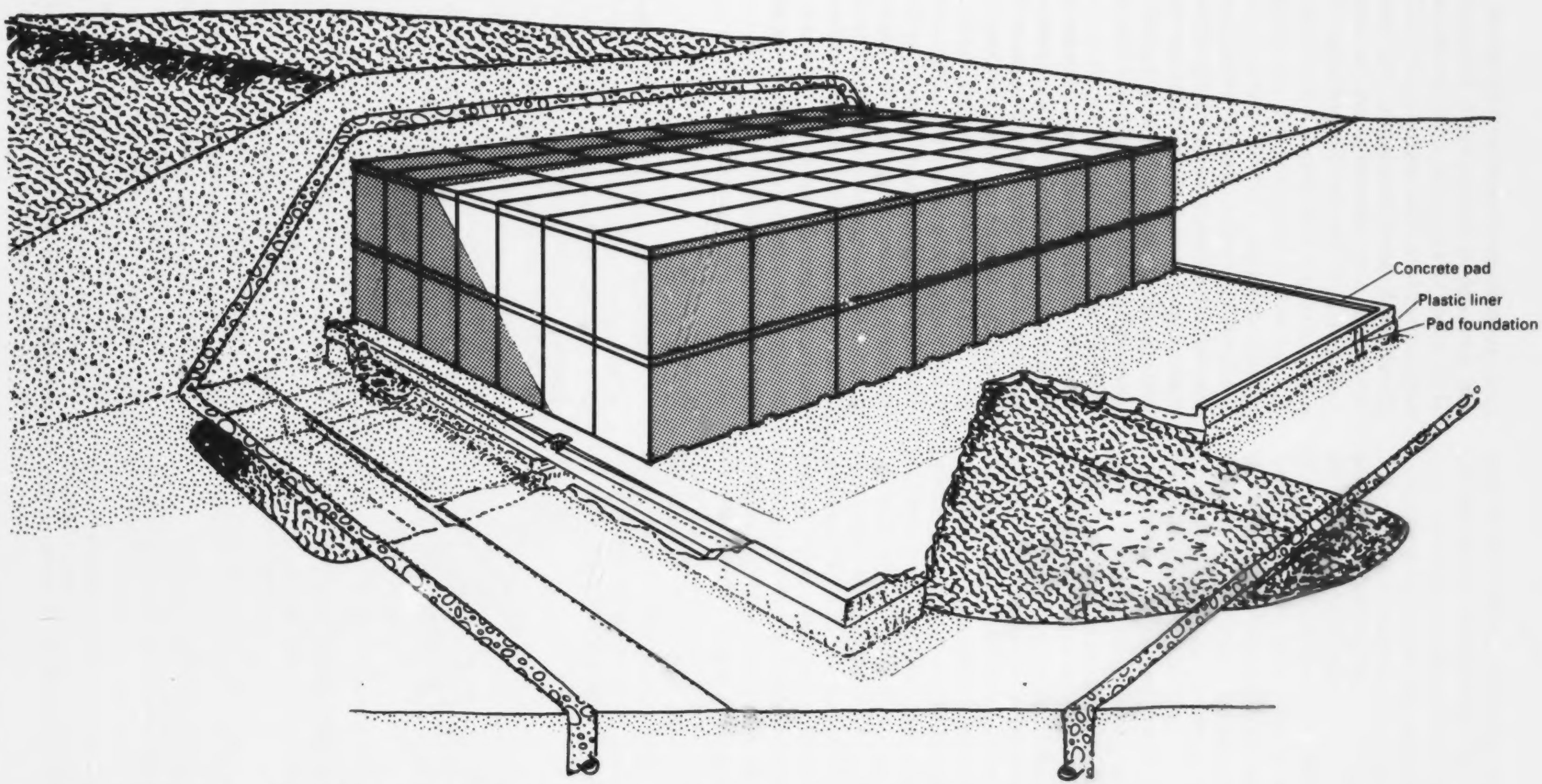

Concrete pad
Plastic liner
Pad foundation

Figure 54. Tumulus being constructed at the Oak Ridge National Laboratory, Tenn. (from Van Hoesen and Clapp, 1987). When the pad is full, an earthen cover will be placed over the modules.

waste was placed into long, shallow trenches 7 m to 10 m deep. Loose or baled waste or wastes in various containers, such as bags, boxes, crates, drums, and liners, were placed in the trench. The containers generally were placed randomly rather than stacked uniformly. Trenches typically were backfilled with previously excavated earth, sometimes the earth was compacted, and then the trench was covered with earth to a minimum of 1 m depth.

Improved shallow-land disposal, as prescribed by the U.S. Nuclear Regulatory Commission (1982), is distinguished from shallow-land disposal as previously practiced, mainly by the fact that an improved shallow-land disposal facility is designed or redesigned and operated to meet the Commission's requirements. These include three principal requirements pertaining to classification of wastes: (1) Low-level radioactive waste must be segregated into three classes, A, B, and C; (2) class B and class C wastes must be in a physically stable form before burial; and (3) burial trenches for class C waste must include a suitable intruder barrier.

Construction basically is a trenchlike excavation to which engineered enhancements are added. The trench floor and walls may be lined with concrete or clay. The floor is sloped for controlled drainage of any liquids to a sump at the low end. Class B and class C wastes are buried in a separate trench from class A waste. Class C waste further is isolated by a thick layer of earth or other fill and by an intruder barrier of concrete or large cobbles. Waste containers are placed carefully into the trench in a prescribed, stable arrangement. Void spaces between containers are filled with soil, sand, grout, or concrete to provide additional stability and structural strength. A thick, engineered, multilayered trench cover, forming a low mound at or slightly above grade, seals the trench.

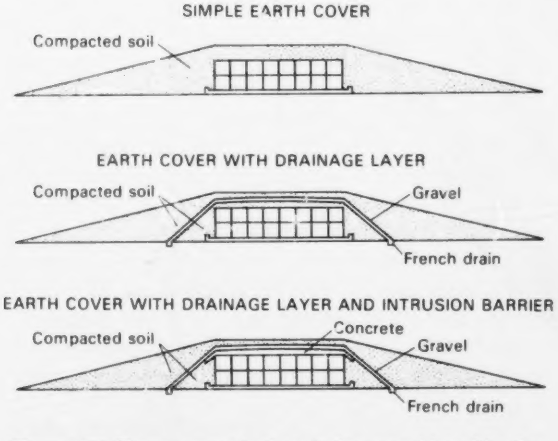


Figure 55. Three cover designs being considered for the tumulus being constructed at the Oak Ridge National Laboratory, Tenn. (modified from Van Hoesen and Clapp, 1987).

An example of an improved burial-trench design is one proposed by Westinghouse Hittman Nuclear, Inc. (1985), for the disposal of solidified evaporator concentrate at the Maxey Flats repository site in Kentucky. The burial-trench design is complex, but basically it is a trench 23 m long, 16 m wide, and 7 m deep. The trench walls and sloped floor are lined with clay. Waste containers are arranged in the trench so as to enable grout walls and columns to be poured into the void spaces. These provide additional structural support for the trench cover. The filled trench is covered with soil, and the soil is covered with a thick mound made up of five layers: (1) A lowermost stone and clay infiltration barrier; (2) a stone drainage layer; (3) a cobble biointrusion barrier; (4) a stone and geotextile filter layer; and (5) a soil layer (fig. 56).

The engineered structural enhancements described for each of the following disposal technologies, when considered for new repository designs, would have to be thoroughly assessed to assure that they would in fact provide the desired improvements and would not inadvertently degrade performance of the repository during its designed duration. Some repair and maintenance of engineered enhancements might be required during the duration of the repository. However, repository failure in the future must be assumed in performance-assessment analyses, and must result in repository-site performance at least as good as that achievable by the site without the engineered enhancements.

Augured Holes

The augured-hole concept, also called shaft disposal, basically is a cylindrical hole augured into the earth. It is a form of shallow-land burial in which wastes are arranged vertically within the hole. Augured holes may be lined or unlined, depending on waste form and characteristics, and on site and soil or rock characteristics. A lining might be a cylindrical shell of concrete, a steel or plastic pipe, or some combination of such materials. A lined hole typically has a barrier, such as a concrete slab, at its bottom and a shielding plug or other closure device at its top (fig. 57). If greater isolation from the land surface is required, the hole could be augured from below grade, such as from the floor of a trench.

An example of the augured-hole concept is the "tile hole," used in Canada for long-term storage of certain medium-level radioactive waste. The version designated "IC–2" is a carbon-steel liner slipped into a larger carbon-steel cylinder embedded in a concrete annulus and base, all arranged coaxially in an augured hole about 8 m deep by 1 m in diameter (Armstrong, 1987). The inner steel liner extends about 8 m downward from land surface and is 0.67 m in diameter. Both steel cylinders have welded, leak-tight base plates. When fully filled with waste, the inner liner is backfilled and capped with concrete. A bolted, gasketed cover plate at the top seals the outer steel cylinder. The dry annular space between the liners periodically is checked for the presence of water or other liquids. The inner liner with its contents is retrievable as a sealed container. Concurrent failure of a waste container and of both cylinders must occur before ground water can contact the waste.

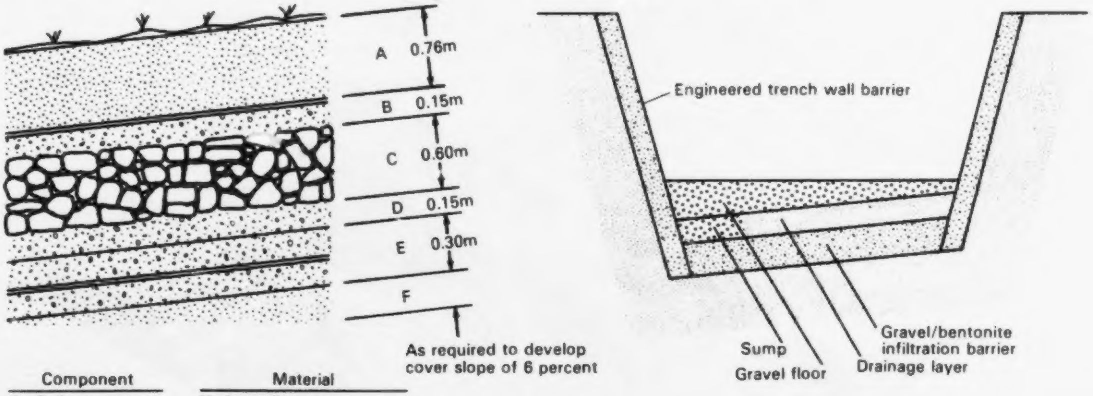
Mined Cavities

The mined-cavity disposal technology consists of the emplacement of low-level radioactive waste in cavities previously excavated by conventional mining techniques for the removal of natural resources. Only underground mines are considered, not surface mines. Cavities newly excavated expressly for the isolation of low-level radioactive waste, although feasible, have received little consideration. Most underground mines in the United States were developed to recover coal, limestone, salt, copper, iron, lead, or zinc. Coal mining has produced the greatest volume of underground space, but coal mines generally are unsuitable for the isolation of low-level radioactive waste because of typically unstable roof conditions and the common presence of ground water. Moreover, methane has the potential to explode and coal to catch fire in worked-out coal mines. Metal mines also generally are unsuitable because of their typically irregular layout and corrosive environments. Limestone and salt mines, however, are potentially suitable because of their more regular rooms and pillars and their broad, straight passages (fig. 58).

The mined-cavity disposal concept has three major components: (1) Surface facilities, (2) underground rooms, and (3) interconnecting shafts and tunnels. Waste is placed in each underground room until the room is filled to capacity; then the room is backfilled and sealed. Interconnecting shafts and tunnels include a main shaft or tunnel for conveying the waste into the mine, probably the original main access shaft or tunnel, and one or more ventilation or emergency shafts or tunnels. Surface facilities consist of a waste receiving area, transfer vehicles, and equipment to move and emplace waste containers, barriers, backfill, and possibly temporary shielding.

Earth-Mounded Concrete Bunkers

The earth-mounded concrete-bunker technology involves four principal elements: (1) Above-ground and below-ground construction; (2) waste-form stabilization through use of modular containers or waste solidification; (3) backfilling with earth, gravel, or concrete; and (4) an earthen cover and multilayered cap over the part above ground (fig. 59). Construction begins with a shallow trench-type excavation. Engineered enhancements, such as reinforced-concrete trench walls and a floor, are added for stability and for better waste confinement. A drainage collection and monitoring system is provided. Higher activity waste is embedded in concrete below


A 0.76m
B 0.15m
C 0.60m
D 0.15m
E 0.30m
F
As required to develop cover slope of 6 percent
Engineered trench wall barrier
Sump
Gravel floor
Gravel/bentonite infiltration barrier
Drainage layer

Component	Material
A Soil cover	Native soil
B Filter layer	Geotextile layer and 19-millimeter-diameter stone
C Biointrusion barrier	Cobbles
D Drainage layer	19-millimeter-diameter stone
E Infiltration barrier	19-millimeter-diameter stone, granular bentonite filler, geotextile layer, 19-millimeter-diameter stone, and granular bentonite filler
F Soil backfill	Native soil

Figure 56. An improved burial-trench concept and detail of trench cover (modified from Westinghouse Hittman Nuclear, Inc., 1985).

ground. Eventually, the below-ground part becomes a solid, monolithic mass that is covered with a layer of concrete at grade. Stabilized waste is systematically stacked onto the monolith, backfilled with earthen material, covered with an earthen mound, and sealed with a multilayered cap. Such a design has been in use for about 20 years in France, where it was designed and developed.

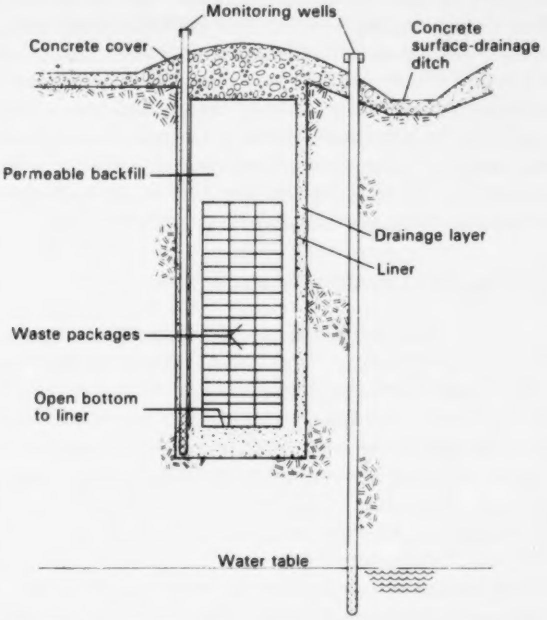

Monitoring wells
Concrete cover
Concrete surface-drainage ditch
Permeable backfill
Drainage layer
Liner
Waste packages
Open bottom to liner
Water table

Figure 57. An augured hole used for burial of low-level radioactive waste (modified from Bennett, 1985).

A similar isolation technology was developed under a U.S. Department of Energy contract (U.S. Department of Energy, 1987). It involves the use of above-ground disposal with an earthen mounded cover for class A waste, and below-ground disposal of class B and class C waste in concrete (the concrete bunker). Two variations of this technology are under consideration. In one, the earth mound is located directly above the concrete bunker, as in the French design. In the other, the earth mound and the concrete bunker are at separate locations. The earth-mound design is the same in both cases. Class A waste first is placed into cylindrical concrete canisters. A gravel pad is prepared at ground level and the canisters are stacked three high on the pad, maintaining an approximate 1:1 slope on the perimeter. Voids between canisters are backfilled with earth, and compacted backfill then is extended over the completed parts to provide a more gradual side slope of 1:2.

The concrete bunker located below the earth mound is a long, narrow concrete trench. Its floor and walls are 0.33-m-thick reinforced concrete. Class B and class C waste containers are placed in the trench, all voids between containers are filled with concrete, and a 0.33-m-thick reinforced concrete roof is put into place to seal the trench. As the trench is sealed, the earth mound above it gradually is extended over the sealed trench.

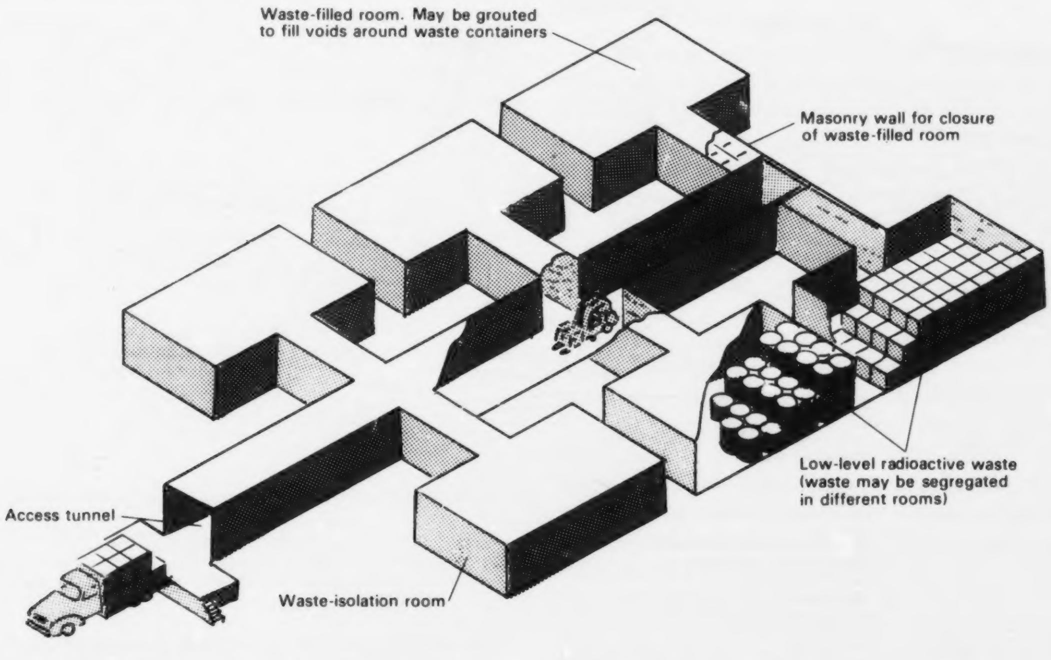

Waste-filled room. May be grouted to fill voids around waste containers
Masonry wall for closure of waste-filled room
Low-level radioactive waste (waste may be segregated in different rooms)
Access tunnel
Waste-isolation room

Figure 58. A conceptual layout for disposal of low-level radioactive waste in a mined cavity in limestone or salt (modified from Bennett and others, 1984).

For the separately located concrete bunker, two reinforced-concrete vaults measuring 7.5 m on each inside edge are constructed on a gravel pad in a 14-m-deep trench. Waste containers are placed into the vaults, all remaining void spaces are filled solid with cement, and the vaults are sealed with a reinforced-concrete roof. Then a 5.5-m-thick earthen cover and cap made up of layers of gravel, sand, clay, backfill, and topsoil is placed over the vaults.

Concrete Vaults

This disposal technology utilizes engineered structures having a floor, walls, roof, and limited access openings. These vaults are constructed in place, either above or below ground. Vaults may be designed in a wide variety of sizes, shapes, arrangements, and materials, but roomlike, reinforced-concrete vaults most commonly are considered.

The above-ground vault technology is different from other disposal technologies in that the vault is not covered or capped with anything other than the roof provided as an integral part of the vault. Such vaults would be readily visible on the landscape. The vault must meet all performance requirements based on design and construction features; that is, the above-ground vault includes no cover or additional barriers to radionuclide migration, inadvertent intrusion, or the effects of long-term weathering or climatic extremes (fig. 60).

The below-ground vault basically is the same as that for the above-ground vault except that the vault is surrounded on all sides by earthen material. The vault must support its weight as well as all cover loads. The vault is not directly exposed to the weather, but it might be exposed to other deleterious conditions such as acidic soil (fig. 61).

An example of a vault design is the Canadian "Quadricell," used for above-ground storage of ion-exchange resins and certain reactor components (Carter, 1981). These reinforced-concrete vaults approximate a cube 7 m on an edge. They are divided into four cells by 0.33-m-thick internal walls. Cylindrical concrete canisters with internal steel liners hold the waste. When filled and closed with a heavy concrete lid, one canister is fitted into each of the four cells and the Quadricell then is sealed with four heavy concrete lids. Even excluding the inner steel liner of the concrete canister, this design provides two independent envelopes with a monitored interspace (fig. 62).

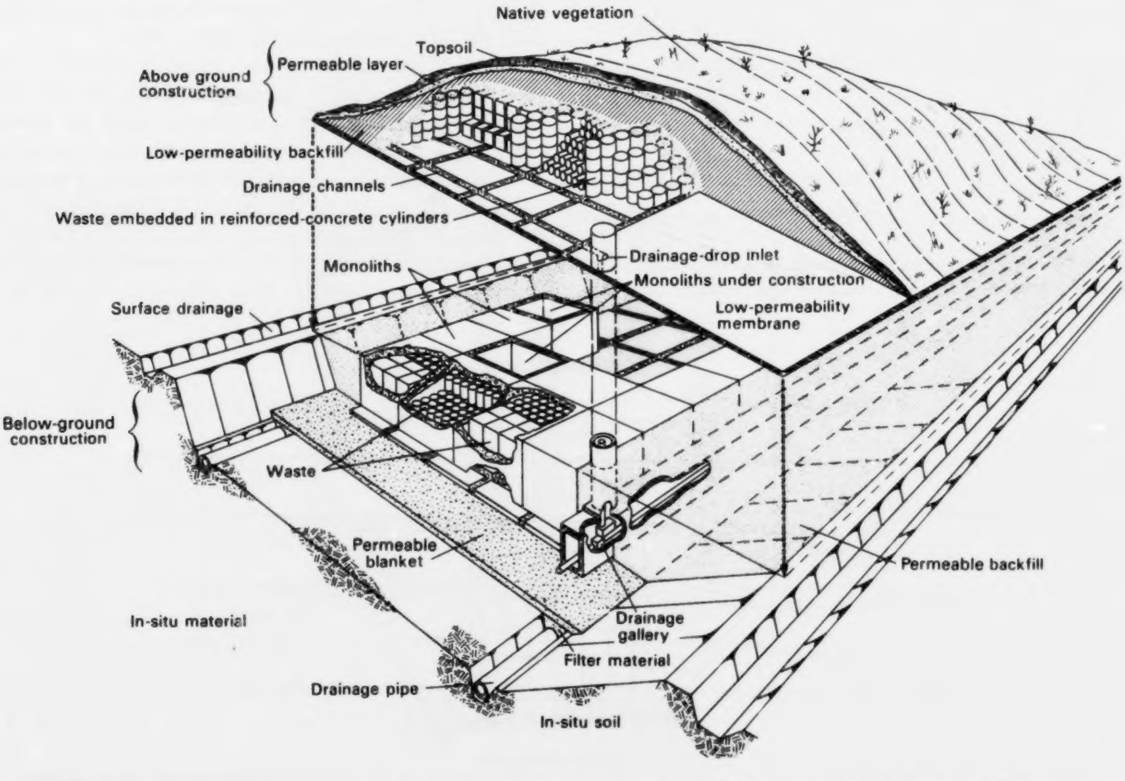

Native vegetation
Topsoil
Permeable layer
Above ground construction
Low-permeability backfill
Drainage channels
Waste embedded in reinforced-concrete cylinders
Drainage-drop inlet
Monoliths under construction
Monoliths
Low-permeability membrane
Surface drainage
Below-ground construction
Waste
Permeable blanket
Permeable backfill
In-situ material
Drainage gallery
Filter material
Drainage pipe
In-situ soil

Figure 59. An earth-mounded concrete bunker (modified from Van Kote, 1982) consists of four parts: (1) Construction above- and below-ground, (2) a solid, stable waste form or modular waste containers, (3) backfill consisting of earth, gravel, or concrete, and (4) a mounded earthen cover and a multilayered cap.

Modular Structures/Concrete Canisters

The modular-structures/concrete-canisters technology utilizes waste containers, most likely made of concrete, that are normally larger than 208–L drums but smaller than vaults. These containers are sealed and emplaced in excavations or into other structures either above or below ground. Modular containers characteristically have structural strength and durability exceeding that of steel drums, are transportable, are not rigidly attached to anything, have a geometry suitable for orderly stacking, and can potentially be mass produced either onsite or offsite. A modular structure or canister contains the waste, provides physical stability that the waste form usually lacks, typically provides radiation shielding by virtue of its material and construction, and may be expected to provide waste containment for long periods of time. Modular structures that are cylindrical in shape commonly are called "modular concrete canisters."

The modules alone do not constitute a complete disposal technology; indeed, they might be considered little more than a means of stabilizing waste forms. A complete modular disposal technology would combine a system of natural or other engineered barriers with the engineered barrier and stability provided by the modules.

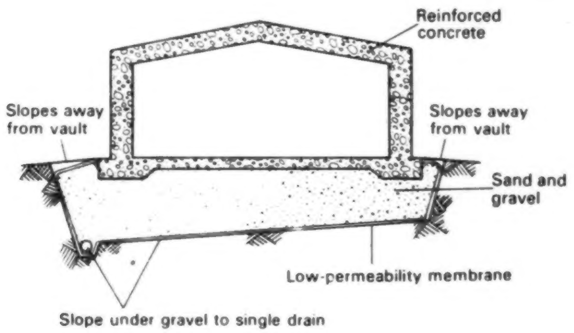


Figure 60. Vault above ground is not capped with earthen material (modified from Bennett and Warriner, 1985).

An example of a low-level radioactive-waste disposal system that incorporates the use of concrete modules either above or below ground is the SUREPAK disposal technology. The SUREPAK module is a 6-sided reinforced concrete module with a cylindrical inside cavity and a sealable concrete lid (fig. 63). It is available in a variety of sizes and wall thicknesses, with capacities of from 3.68 to 6.23 m^3. In this disposal system (Westinghouse Electric Corp., 1985b) all voids in filled modules are grouted with cement. Loaded modules would weigh from 15.9 to 43.5 t. The bottoms of all modules have a concave shape to assure that the weight of stacked modules is transmitted directly to the load-bearing walls of the modules below. All modules are reinforced with wire mesh, rebar, or in some cases, fiberglass. They are fitted with a siphon drain for collecting liquid samples if desired.

For the below-ground disposal option, filled and sealed modules are stacked three layers high on a gravel pad in a shallow trench. Their hexagonal shape allows little void space between them. As the trench is filled, an earthen cover is placed over the top layer of modules. The cover is capped with layers of silt, gravel, and riprap graded to slope slightly outward from the trench centerline (Westinghouse Electric Corp., 1985a).

For the above-ground disposal option, a reinforced-concrete pad is constructed on grade. The pad is gently sloped and has a perimeter curb for drainage collection. Filled and sealed modules then are stacked two layers high on the pad, and the stack is covered with native soil in a mounded shape. A four-layer cap about 2 m thick, consisting of gravel, sandy clay, cobbles, and native soil, then is placed over the mound (Westinghouse Electric Corp., 1985b). This option is similar to the

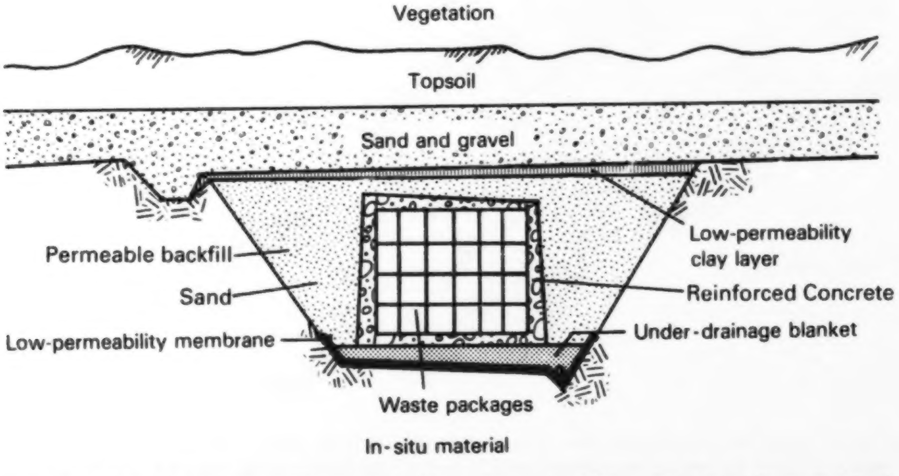
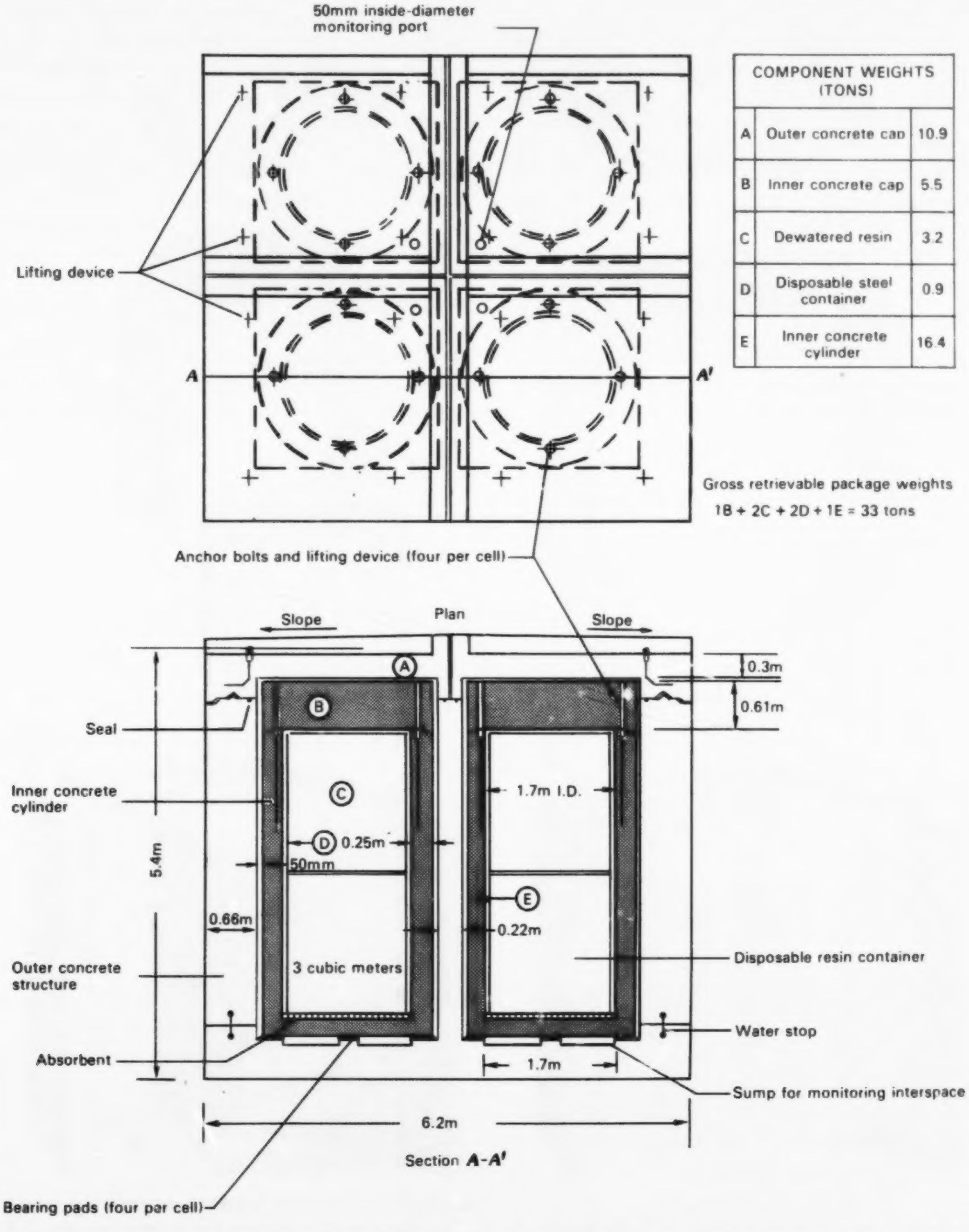


Figure 61. Vault below ground is capped with earthen material (modified from Bennett, 1985).

tumulus being constructed at the Oak Ridge National Laboratory (fig. 54).

Storage/Monitor/Retrieve Units

The present (1987) trend of using more engineered structures in isolation technologies is likely to encourage a variety of new designs during the next few years. Most designs may be expected to be variations and refinements of the basic designs already described, but some will incorporate design features of sufficient originality and uniqueness as to be patentable. One such design already has been developed (Galloway and others, 1985). The overall objective is to separate class A waste from class B


50mm inside-diameter monitoring port
Lifting device
A
A'
Anchor bolts and lifting device (four per cell)
Plan
Slope
Slope
A
B
C
D
E
0.3m
0.61m
Seal
Inner concrete cylinder
1.7m I.D.
0.25m
50mm
5.4m
0.66m
0.22m
Outer concrete structure
3 cubic meters
Disposable resin container
Water stop
Absorbent
1.7m
Sump for monitoring interspace
6.2m
Section A-A'
Bearing pads (four per cell)

COMPONENT WEIGHTS (TONS)		
A	Outer concrete cap	10.9
B	Inner concrete cap	5.5
C	Dewatered resin	3.2
D	Disposable steel container	0.9
E	Inner concrete cylinder	16.4

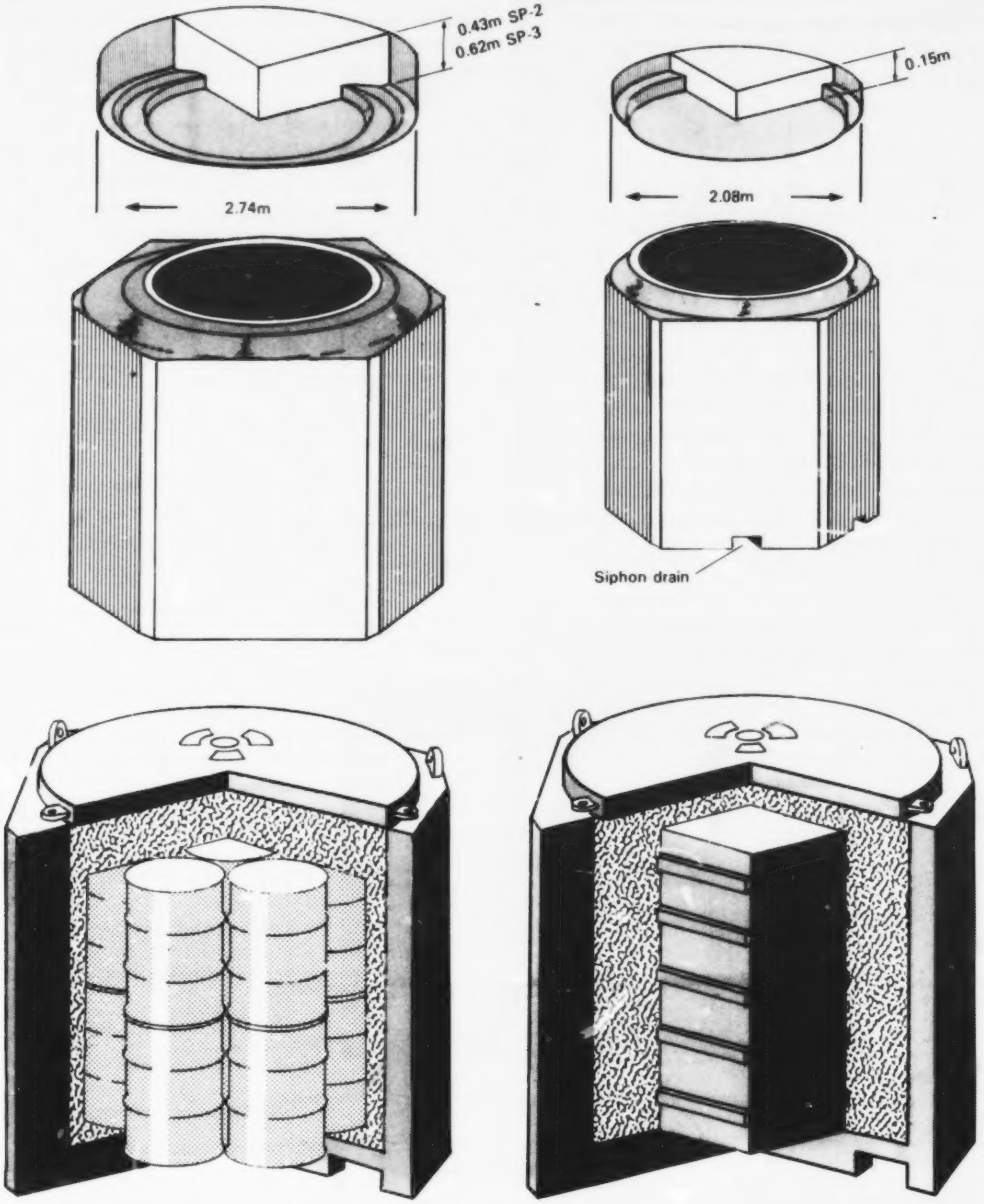
Gross retrievable package weights

1B + 2C + 2D + 1E = 33 tons

Figure 62. Ontario Hydro's above-ground vault, the Quadricell (modified from Carter, 1981). Waste in concrete canisters with internal shell liners; canisters in reinforced concrete.

and class C wastes, and to isolate the large-volume, low-level class A waste in a unit of the below-ground vault type. The small remaining volume of high-activity class B and class C wastes, in shipping containers, then is placed into Store/Monitor/Retrieve units.

The principal component of a Store/Monitor/Retrieve unit is a cylindrical, double-walled steel canister. Containers of class B and class C wastes are stacked in the inner cylinder of the canister. This inner cylinder then is sealed, providing a dry, corrosion-free environment around the waste. The outer cylinder also then is closed and sealed; its closure results in a sealed void between the inner and outer walls. This void extends across the bottom, up the annulus between the walls, and across



SUREPAK PLUS DRUMS

SUREPAK PLUS LOW SPECIFIC-ACTIVITY BOXES

Figure 63. The SUREPAK module, lid designs, and filled modules (modified from Westinghouse Electric Corp., 1985a). The module is made of reinforced concrete and has a sealable concrete lid.

part of the top (fig. 64). The void then is completely filled with a silicon-based monitoring fluid that is continuously circulated through appropriate piping to radiation monitors and back, in a closed system. Any leakage from the inner cylinder would promptly be detected by the monitors, and the leaking cylinder could be identified, isolated, and retrieved for repair, if necessary. Leakage of monitoring fluid through the outer wall or some part of the monitoring system would be detected by fluid-level sensors. All monitoring is under computer control. Four such canisters then are placed into a 0.6-m-thick reinforced-concrete structure (fig. 65). After flow-line interconnections are made, a concrete shielding cover is placed above the canisters. This structure forms the basic, repeatable Store/Monitor/Retrieve unit, which can be located either above or below ground. Suitable cover is provided over the units in both cases.

Each of these eight disposal technologies offers potentially suitable engineered enhancements for safe disposal of low-level radioactive waste. At the same time, each may not be suitable in some geohydrologic environments. All the disposal methods incorporate some combination of natural and engineered barriers, structural components or containers, and environmental monitoring. Natural materials such as clay, soil, gravel, and cobbles most commonly are used in these disposal methods, but some include steel, plastic, and geotextile. Reinforced concrete is by far the preferred structural material. Except for mined cavities, all technologies place waste on or within 17 m of the Earth's surface. Although emphasis in this paper is on engineered disposal technologies, site geohydrology must be fully understood at any designated low-level radioactive-waste repository site and the disposal technology, the engineering, design, and the operation of the repository site must be compatible with the natural conditions at the site in order to effect satisfactory containment of the waste. The reader is referred to other papers in this volume, particularly those describing existing low-level radioactive-waste repository sites, to gain an appreciation of the problems relating to the interaction of the local geology and hydrology with the design, construction, and operation of such sites.

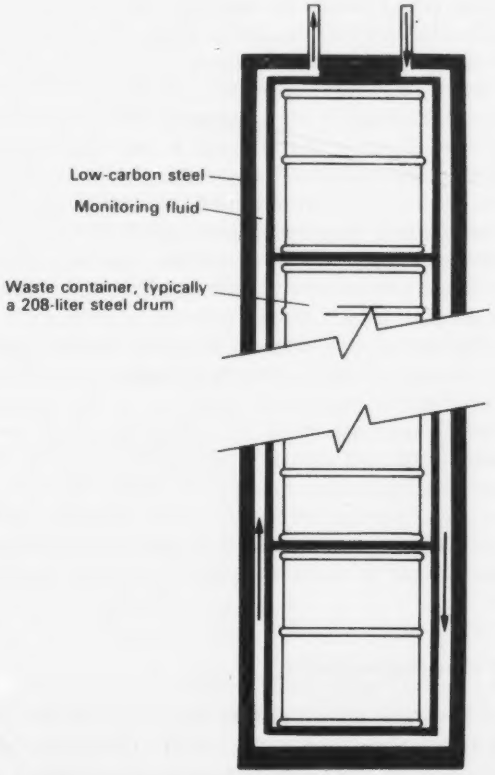


Figure 64. The Store/Monitor/Retrieve double-walled steel canister (modified from Galloway and others, 1985). Arrows indicate direction of movement of the monitoring fluid.

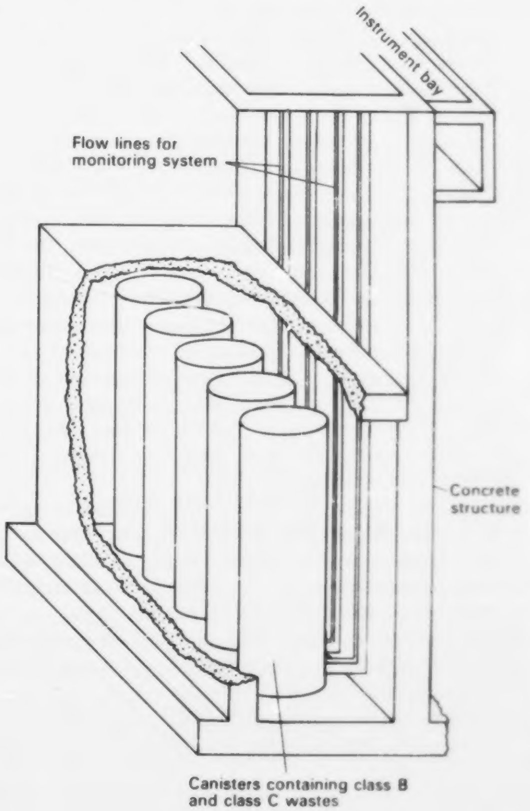

Instrument bay
Flow lines for monitoring system
Concrete structure
Canisters containing class B and class C wastes

Figure 65. The Store/Monitor/Retrieve unit (modified from Galloway and others, 1985), showing canisters in 0.6-m-thick reinforced-concrete structure.

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Difficulties with Above Water-Table Disposal of Low-Level Radioactive Waste in Areas Having Rapid Accretion Rates

By Vernon T. Ichimura

When the first six commercially operated low-level radioactive-waste repository sites were constructed, there were no regulations governing the siting criteria. Each State was allowed to determine its own regulations, provided that these States assumed the overall responsibility for the regulation of the site. Therefore, the development of burial practices and regulations governing burial operations have been in constant evolution. Furthermore, with the passage of the Low-Level Radioactive Waste Policy Act of 1980, each State has now become responsible for the low-level radioactive waste generated by nondefense facilities within its boundaries or within areas of Congressionally approved interstate compacts (Robertson, 1984).

In order to help regulate State and regional low-level radioactive-waste repository sites, the U.S. Nuclear Regulatory Commission has issued a technical position paper on site suitability, selection, and characterization requirements (Siefken and others, 1982). This document serves as a technical interpretation of Federal regulations that became effective in January 1983 (U.S. Nuclear Regulatory Commission, 1982). These regulations specify minimum geotechnical requirements for site suitability, design, operations, closure, and monitoring and is discussed in detail in the paper by Weber (this volume).

The purpose of this paper is to evaluate several repository-site requirements concerning burial of waste in the unsaturated material above the zone of water-table fluctuation and to provide information that will aid in identifying a potentially licensable repository site. A simplified analytical and generic approach will be used to demonstrate siting difficulties associated with above water-table burial of low-level radioactive waste in humid environments using the technical requirements included in the Federal regulations. Because of the simplified analytical approach used in this paper, there are no directly associated repository-site examples of the theoretical conditions presented in this paper. However, the concepts presented are based on the collection of data obtained during site-evaluation studies in semiarid environments and at currently (1987) operated repository sites.

Technical Requirements

Favorable characteristics and problems associated with burial above the water table at presently (1987) established low-level radioactive-waste repository sites have contributed to the selection of current requirements for new sites. Most of the problems encountered at present repository sites have been caused by infiltration of water into the burial trenches and subsequent transport of waste away from the trenches. The problems of low-level radioactive-waste burial at several repository sites in humid environments are reviewed in papers in this volume, namely sites near Sheffield, Ill., by Healy; at the Oak Ridge National Laboratory, Tenn., by Webster; near West Valley, N.Y., by Randall; and at Maxey Flats, Ky., by Lyverse.

In contrast, the lack of waste migration at the repository sites near Beatty, Nev., and Hanford, Wash., was attributed to the absence of water because both sites are situated in arid environments and are constructed in coarse-grained, unconsolidated sediments (Robertson, 1984; Fischer, 1986). Gaynor (1984) estimated the annual infiltration rate at the repository site near Beatty to be 0.06 cm. In general, depth to the water table ranged from 0 to 20 m at sites in humid environments; the depth to water is about 100 m at the sites in arid environments.

Water-Table/Hydraulic–Conductivity Relation

One of the most probable ground-water flow patterns will be used to investigate the relation between an average water-table elevation and properties of the porous media. A potential site for the burial of low-level radioactive waste above the water table is shown in figure 66. In order to minimize downward waste migration, the geologic unit underlying the burial trenches should have a lesser hydraulic conductivity than that of the surficial geologic unit into which the burial trenches will be excavated. Such conditions are common where weathered material overlies bedrock.

The Dupuit approximation that is used to solve this hypothetical flow problem is based on the assumptions that: (1) Most water-table slopes are small (Bear, 1972); (2) the velocity of the flow is proportional to the tangent of the hydraulic gradient; and (3) the flow is horizontal and uniform so the discharge per unit width is:

$$q_x = -Kh\frac{dh}{dx} \qquad (1)$$

where

q_x = discharge per unit width,
K = hydraulic conductivity,
h = hydraulic head, and
x = distance at right angles from the stream.

Equation 1 is a form of Darcy's law (Darcy, 1856). The hydraulic conductivity is related to the permeability, which is a function of the porous medium by $k=(K\mu)/(\rho g)$, where μ is the fluid viscosity, ρ is the fluid density, and g is the acceleration of gravity.

Equation 1 alone is insufficient to describe the flow field because there are two unknowns: $q_x=q_x(x,t)$ and $h=h(x,t)$, in one equation. A second equation, the continuity equation, accounts for the conservation of mass and can be written as follows:

$$\frac{-\partial q_x}{\partial x} + N = n_e\frac{\partial h}{\partial t} \qquad (2)$$

where N is the accretion rate, and n_e is the effective storage porosity that is available for additional water storage based on the specific-yield concept (Todd, 1980). Substituting equation 1 into 2, the result is:

$$\frac{\partial}{\partial x}\left[Kh\frac{\partial h}{\partial x}\right] + N = n_e\frac{\partial h}{\partial t} \qquad (3)$$

By assuming steady flow and constant K, $h=h(x)$, equation 3 becomes:

$$\frac{K}{2}\frac{\partial^2(h^2)}{\partial x^2} + N = 0\ . \qquad (4)$$

Integrating twice, the result is:

$$h^2 = -\frac{N}{K}x^2 + ax + b \qquad (5)$$

where a and b are constants of integration. Using the boundary conditions from figure 66: $x=0, h=0$ and $x=L$, $h=0$.

Equation 5 then becomes:

$$h = \left(\frac{N}{K}(L-x)\,x\right)^{1/2}\ . \qquad (6)$$

Solving for the maximum value of h in the domain $0<x<L$ results in:

$$h_{max} = \left(\frac{N}{K}\frac{L^2}{4}\right)^{1/2}\ . \qquad (7)$$

Equations 6 and 7 are subject to limitations and errors that are discussed in Bear (1972).

Equation 7 is illustrated in figure 67 for different accretion rates, N. The term H/x in figure 67 is an indicator for the slope of the theoretical water-table surface, where H is the maximum height of the water table above the stream (at the ground-water divide), and x is $L/2$, the distance from the stream to the ground-water divide (fig. 66). According to figure 67, the slope of the water table increases with decreasing hydraulic conductivity. The hydraulic conductivity of the burial zone should be small, for example, less than 10^{-5} cm/s, which would help ensure waste containment and provide slow rates of radionuclide transport from the repository site. However, a small hydraulic conductivity of host media has created problems at most of the existing repository sites. Furthermore, typical accretion rates at repository sites in humid environments have been estimated to be greater than 2.5 cm/yr, and, according to figure 67, H/x is 9×10^{-2} for $K=10^{-5}$ cm/s and $N=2.5$ cm/yr. This simply means that the average land-surface slope must exceed H/x to provide adequate separation between the water table and the bottom of the burial zone. Current repository sites have land-surface slopes in the operations area that are less than 5×10^{-2} to minimize erosion, and typical burial trenches require a minimum of 10 m of unsaturated zone. Generally, the slope of the land surface, when measured from the drainage divide to the discharge area, is greater than the slope of the land surface at the operations area of the repository sites. At existing repository sites, the estimated H/x values are about 4×10^{-2} at the site near Sheffield, Ill. (Foster and others, 1984a, fig. 8), 1×10^{-1} at the site near West Valley, N.Y. (Prudic, 1986, fig. 15), and 2×10^{-2} at the site near Barnwell, S.C. (Cahill, 1982, fig. 18). However, precise values of H/x vary as much as 1 order of magnitude depending on the measurement locality. For example, H/x ranged from 2×10^{-2} to 4×10^{-2} at the site near West Valley, N.Y., as shown in Prudic (1986, figs. 20 and 13, respectively).

Transient Response of Water Table

To show that the time rate of the water-table rise is greatest when the specific yield is small, we will begin with equation 3. Equation 3 is nonlinear and has a few known solutions. In this paper we have chosen to linearize equation 3 because we are only interested in a measure of the short time rate of the variance of the water-table rise.

To linearize equation 3, we assume that the change in transmissivity is small compared to the average transmissivity, so $Kh\cong K\bar{h}$. Therefore, equation 3 becomes:

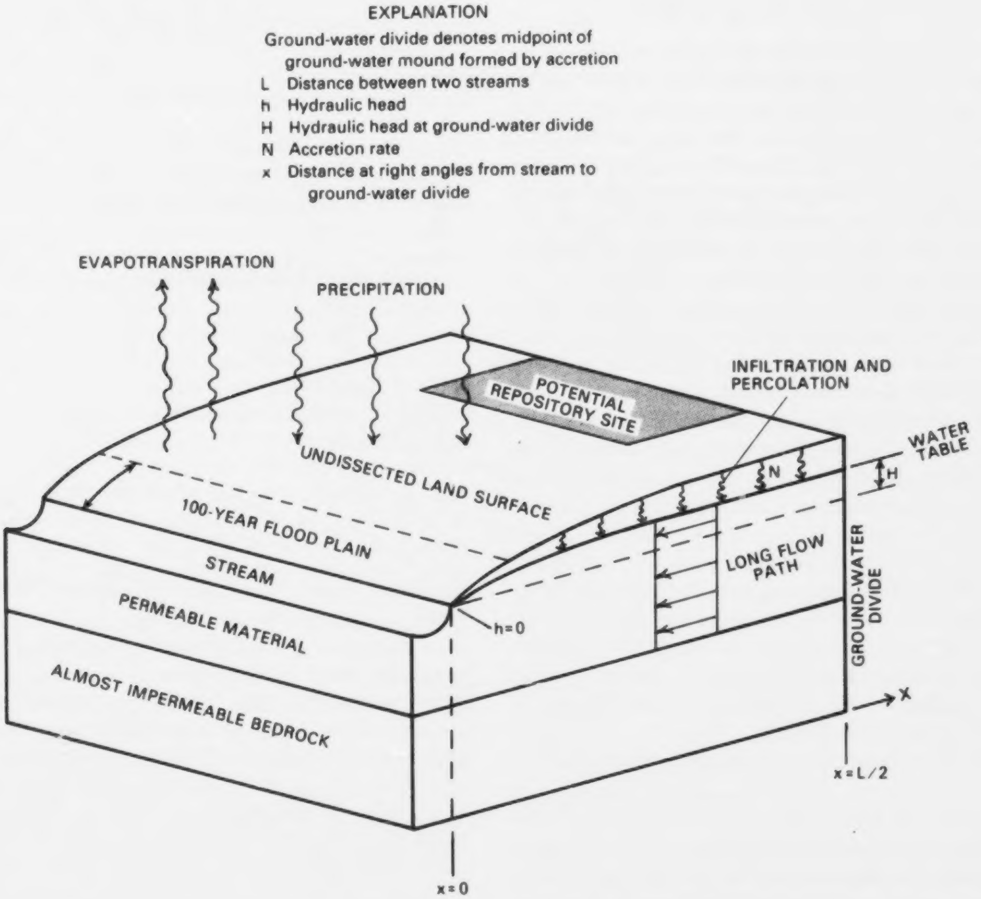
EXPLANATION
Ground-water divide denotes midpoint of ground-water mound formed by accretion
L Distance between two streams
h Hydraulic head
H Hydraulic head at ground-water divide
N Accretion rate
x Distance at right angles from stream to ground-water divide
EVAPOTRANSPIRATION
PRECIPITATION
POTENTIAL REPOSITORY SITE
INFILTRATION AND PERCOLATION
WATER TABLE
N
H
UNDISSECTED LAND SURFACE
100-YEAR FLOOD PLAIN
STREAM
PERMEABLE MATERIAL
ALMOST IMPERMEABLE BEDROCK
LONG FLOW PATH
GROUND-WATER DIVIDE
h=0
X
x=L/2
x=0

Figure 66. Potential site for burial of low-level radioactive waste above the water table and boundary-condition definition. The geologic unit underlying the burial trench should have a lesser hydraulic conductivity than that of the surficial geologic unit into which the burial trench will be dug in order to minimize the waste migrating downward.

$$\frac{K\bar{h}}{n_e}\frac{\partial^2 h^2}{\partial x^2} + \frac{2\bar{h}}{n_e}N = \frac{\partial h^2}{\partial t} \ . \qquad (8)$$

Hantush (1967) and Marino (1967) solved equation 8 for the condition that accretion only occurs in Region I of figure 68. As shown by Bear (1972), the statement of the problem for Region I is:

$$\frac{K\bar{h}}{n_e}\frac{\partial^2 h_1{}^2}{\partial x^2} + \frac{2\bar{h}}{n_e}N = \frac{\partial h_1{}^2}{\partial t} \ . \qquad (9)$$

where

$$N \ = \ >0 \text{ for } t > 0$$
$$h_1 \ = \ h_1(x, t) \text{ in } 0<x<L$$

$$Kh_1\frac{\partial h_1}{\partial x}\bigg|_{x = 0,\, t>0} = 0$$

$$h_1(x, 0) = h_i$$

For Region II:

$$\frac{K\bar{h}}{n_e}\frac{\partial^2 h_2{}^2}{\partial x^2} = \frac{\partial h_2{}^2}{\partial t} \ . \qquad (10)$$

where

$$h_2\,(x, 0) \ = \ h_i$$
$$h_2\,(\infty, t) \ = \ h_i$$
$$h_1\,(L, t) \ = \ h_2\,(L, t)$$

and

$$Kh_1\frac{\partial h_1}{\partial x}\bigg|_{x = L,\, t\geqq 0,} = Kh_2\frac{\partial h_2}{\partial x}\bigg|_{x = L,\, t\geqq 0.} \qquad (11)$$

Equation 9 describes the development of a ground-water mound owing to instantaneous accretion throughout a region $0 \leqq x \leqq L$. The solution of equation 9 for Region I, according to Hantush (1967, eq. 2) is:

$$h_1{}^2 - h_i{}^2 = \frac{N}{K}vt\left[2 - 4i^2 \ \mathrm{erfc}\left(\frac{L-x}{\sqrt{4vt}}\right) - 4i^2 \ \mathrm{erfc}\left(\frac{L+x}{\sqrt{4vt}}\right)\right] , \qquad (12)$$

where $v = \dfrac{K\bar{h}}{n_e}$

and i^2 (erfc) is the second repeated integral of the complement of the error function. According to Marino (1967), the solution given by equation 12 is similar to experimental results, provided that $N \leqq 0.2\,K$ and $(h - h_i) \leqq 0.5h_i$.

The maximum height of the water table under the pond will occur in Region I at $x=0$, at the center line of the pond. For sufficiently large values of L and small values of t such that:

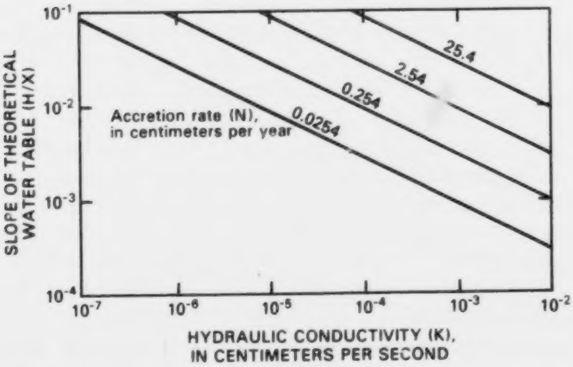

Figure 67. Relation of slope of theoretical water table to hydraulic conductivity for different accretion rates. The slope of the water table increases with decreasing hydraulic conductivity.

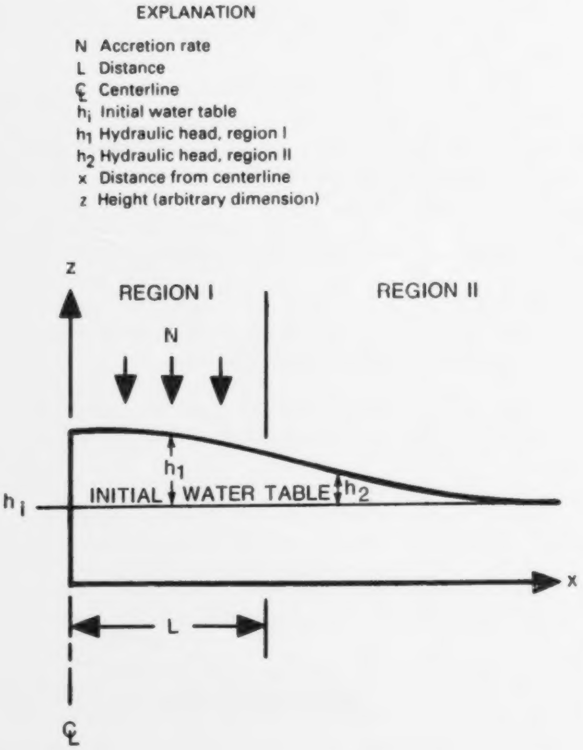
EXPLANATION
N Accretion rate
L Distance
℄ Centerline
hᵢ Initial water table
h₁ Hydraulic head, region I
h₂ Hydraulic head, region II
x Distance from centerline
z Height (arbitrary dimension)
z
REGION I
REGION II
N
h₁
h₂
hᵢ
INITIAL WATER TABLE
x
L
℄

Figure 68. Development of a ground-water mound under a pond of infinite length and width 2L. Accretion occurs only in region I, not in region II.

$$\frac{L \pm x}{\sqrt{4\upsilon t}} > 2,$$

then

$$4i^2\mathrm{erfc}\,\frac{L \pm x}{\sqrt{4\upsilon t}} = < 0.0008$$

(Carslaw and Jaeger, 1959, App. II, table I), and because $\bar{h} \cong h_i$, then equation 12 reduces to:

$$h_1(t)=\left(\frac{2Nh_i}{n_e}t + h_i^2\right)^{1/2} . \qquad (13)$$

Equation 13 represents the water-table rise at small values of t under sufficiently wide water basins with constant N. This expression contains no hydraulic-conductivity variable because the early water-table rise is only due to accretion, N, and is yet to be affected by sufficient lateral flow which is governed by the hydraulic conductivity of the medium. Equation 13 indicates that the time rate of water-table rise will increase as n_e decreases. As an example, figure 69 shows the water-table rise for values of small t when $L=4\times10^4$ m, $N=10^{-6}$ cm/s, $K=10^{-5}$ cm/s, and $h_i=1{,}000$ cm. In summary, with all conditions except n_e being equal, the magnitude of the water-table rise is greatest when n_e is smallest.

Discussion

Equations 7 and 11 are the result of simplification of flow in a porous media throughout a weathered profile underlain by almost impermeable bedrock. Because equations 7 and 11 were derived using the Dupuit approximation, they cannot be applied to a region where the vertical-flow component is substantial. Furthermore, equation 3 is not valid near a stream or a ground-water divide; this equation also cannot be used to describe flow when there is substantial leakage through the underlying bedrock. Equation 7 is a conservative estimate because flow to smaller local streams, leakage through the underlying bedrock, and increases in evapotranspiration as the water table approaches the land surface are not considered.

Likewise, the above equations represent a simplification of typical weathered profiles that may consist of a surface layer of humus-rich soil that grades downward to less weathered media, until the bedrock is reached (Hillel, 1980). If the permeability of the bedrock is

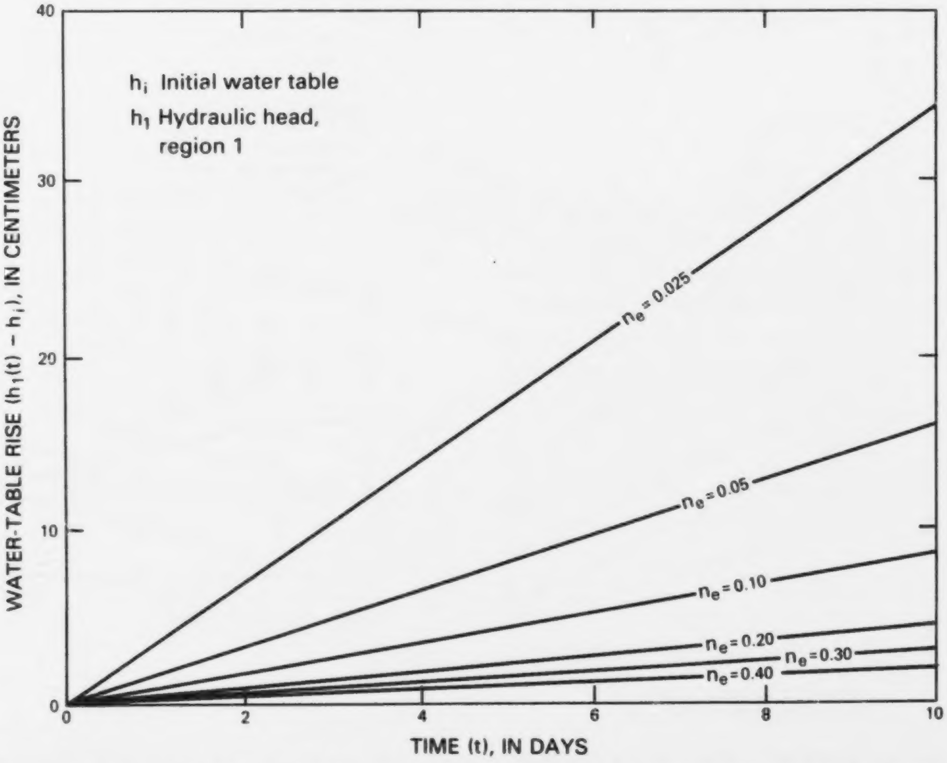

Figure 69. Example of time rate of water-table rise caused by accretion in porous media having different values of n_e. The magnitude of the water-table rise is greatest when n_e is smallest. n_e is effective storage porosity available for additional water storage.

negligible, the permeability of the resultant soil profile likely will decrease exponentially with depth. These permeability variations have been noted over shale (Roggenthen and others, 1985) and metamorphic and plutonic rocks (Davis and DeWiest, 1966). Such a weathering profile will enhance lateral migration of waste near the top of the water table at the land surface. Furthermore, such a profile will increase the likelihood of a "bathtub effect" where burial trenches fill with water and overflow, as illustrated in Duguid (1979). Additionally, lateral migration of ground water near the land surface allows for ease of waste-migration detection but decreases the isolation potential of the repository site.

The relations of water-table height and fluctuation to hydraulic conductivity, K, and effective storage porosity, n_e, are given by equations 7 and 11, respectively. To minimize potential waste migration, K should be less than 10^{-5} cm/s. A value of K of less than 10^{-5} cm/s is suggested for above water-table burial because such a value is commonly characteristic of a soil profile consisting of silt or silty sand. Typical n_e values range from 0.03 to 0.40. Porous media that have small K values have associated lesser porosity and, consequently, smaller n_e values. For example, typical n_e values for clay, silt, and till are 0.03, 0.08, and 0.06, respectively (Todd, 1980). Therefore, below ground and above water-table burial of waste becomes difficult to impossible under the current (1987) regulations when the accretion rate, N, is greater than 2.5 cm/yr, as predicted by equations 7 and 11. Such values of N are likely throughout much of the humid eastern United States. Deep water tables in humid areas usually occur in coarse-grained materials having large K values (Cartwright and others, 1981). Furthermore, these shallow-water-table geohydrologic conditions were noted during reconnaissance studies for repository sites in southern Canada (Cherry and others, 1979); contrasting conditions also were detected during reconnaissance studies of arid environments where thick unsaturated zones are known to exist (Langer and Bedinger, 1985).

In summary, fine-grain sediments with minimal hydraulic conductivity in humid environments have water tables near the land surface. The depth to the water table will decrease as the hydraulic conductivity of the sediments decreases when comparing land areas having similar accretion rates and topography. Furthermore, the fluctuation of the water table is greatest when the available pore size is smallest, such as in fine-grain sediments; depending on the volume of accretion, ground water may overflow onto the land surface. Therefore, if the geologic medium is chosen to bury waste, it also will contain the water in the form of a large mound controlled by the topography because the topography determines the point of discharge.

In contrast, when the hydraulic conductivity of the host media is greater, the movement of water is less restricted and the relief of the ground-water mound is smaller, but the obvious tradeoff is potentially faster migration rates from the repository site. The advantages, however, are: (1) The potential for migration is decreased because the waste remains in the unsaturated state, and (2) the potential for ephemeral ground-water discharge to the land surface near the repository site is minimized because the water table tends to be farther from the land surface.

Alternative below water-table burial of low-level radioactive waste has been suggested by Cherry and others (1979), who propose to achieve waste isolation below the water table in a geomorphically and seismically stable area where diffusion transport dominates, and where the regional flow pattern is such that, if leakage occurs, waste will not contaminate water-supply aquifers and enter the biosphere.

Conclusions

Simplified theoretical estimations demonstrate that above water-table burial of low-level radioactive waste is difficult in porous media with minimal permeability and specific yield when accretion rates exceed 2.5 cm/yr. Siting either above or below the water table is mandated by Federal regulations. Porous media with minimal permeability usually has associated minimal specific yield and causes greater fluctuations in the water table, thereby making prior proof of compliance more difficult.

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Thoughts on Geohydrologic Characterization for Prospective Low-Level Radioactive-Waste Repository Sites

By Edwin P. Weeks

Since the advent of the atomic age during World War II, low-level radioactive wastes have been buried at several repository sites throughout the United States. During the early years, such burial was conducted with little concern for the potential for the discarded radionuclides to migrate from the repository to the environment. As the scientific community and society have become cognizant of the potential health hazards of exposure to radionuclides, land burial has been scrutinized with ever-increasing diligence, and repository-site selection has become, at times, an emotional issue.

Many existing repository sites have been closed, and the ones that remain open are used to their physical or politically mandated capacity. Moreover, low-level radioactive-waste isolation has been legislatively mandated as a State and regional problem. Consequently, new repository sites are needed in most regions of the country. The following discussion presents some thoughts and concepts regarding geohydrologic investigations at prospective repository sites.

The overall objectives of geohydrologic characterization of prospective repository sites are to ensure that conditions at the site are adequate to prevent exhumation of the waste by erosion or other geologic processes and to provide a long flow path through the unsaturated and saturated zones from the repository site to the point of ground-water discharge. In addition, the geohydrology at the repository site should be sufficiently simple that the flow path and point of discharge of the leached radionuclides, along with the potential traveltime, can be identified with reasonable confidence.

A major concern in these natural-site investigations is that installation of a repository may greatly alter the geohydrology of the repository site, as discussed by

Webster in the chapter entitled "Burial Grounds for Low-Level Radioactive Waste at Oak Ridge National Laboratory, Tennessee" in this report. Thus it is important that the investigative team not only describe and quantify flow under natural conditions, but they should also anticipate and estimate the magnitude of likely changes induced by the repository.

For the focus of this paper, the geohydrologic characterization will be divided into three aspects: (1) Surface-water hydrology, (2) unsaturated-zone hydrology, and (3) saturated-zone hydrology.

Surface-Water Hydrology

A major premise regarding surface water at prospective repository sites is that there should be none. Regulations state that the repository site should not be in a 100-year flood plain, in a wetland, or near an ephemeral stream channel. It is implied that the repository site should be located near topographic divides to minimize overland flow crossing the site. Although I have not specialized in the surface-water discipline, it seems to me that these restrictions can be met by inspection of prospective repository sites.

Unsaturated-Zone Hydrology

Unsaturated zone hydrology is complicated in detail, as measurement of the hydraulic-head potential in unsaturated media is difficult. In addition, properties governing hydraulic conductivity and specific moisture capacity depend on soil-moisture content or hydraulic head in an extremely nonlinear way and on whether the material is wetting or drying. Because of these complications, it is essential that only the important aspects of unsaturated-zone flow be considered in evaluating a prospective site for a repository.

One aspect that allows for simplified treatment of unsaturated-zone flow is that its direction usually is known. In the absence of stratigraphy that would produce a perched saturated zone or a capillary barrier to deep percolation, unsaturated-zone flow generally will be vertically downward. Thus, in many cases, a strategy for characterizing the geohydrology of a prospective repository site might include first determining whether perched saturated zones exist, are likely to occur during prolonged periods of exceptionally wet weather, or might occur as a result of increased recharge owing to repository construction. Should such zones be present or be likely to occur, the consequences of downdip movement by saturated flow need to be considered. In some cases, a perching layer might divert drainage from the prospective repository to a nearby hillside, greatly decreasing traveltime of leachates from the repository to the accessible environment. In other cases, such movement might increase such traveltime.

If the potential for the development of perched ground water is minimal, residence time of potentially contaminated leachates in the unsaturated zone can be delimited from estimates of deep percolation from the prospective repository, water stored in the unsaturated zone beneath the prospective repository, and limiting assumptions concerning the nature of flow and transport in the unsaturated zone. As an example, a maximum residence time can be estimated by assuming that the deep percolation completely displaces the moisture immediately in front of it—the "piston displacement" concept. Under these conditions, the unsaturated-zone residence time can be computed by dividing the unsaturated-zone storage by the rate of deep percolation. At the other extreme, if flow is assumed to occur in macropores, residence time in the unsaturated zone is virtually zero.

These considerations indicate that, if residence time in the unsaturated zone is to be a primary consideration in accepting the site for a repository, water flux through the prospective repository, soil-moisture storage, and the predominant flow mechanism need to be identified.

Reliable estimates of water flux through a prospective repository are sometimes difficult to obtain, as the presence of the as-yet-unbuilt repository may greatly alter the deep percolation from that occurring under natural conditions. Nonetheless, estimates of recharge for natural conditions at the prospective repository site may provide a logical starting point for predicting deep percolation under repository conditions. A short list of techniques that might be used to evaluate recharge include: water-budget methods and water-balance methods; monitoring of moisture movement; and evaluation of tracers, both environmental and those that might be applied during the study.

Water-budget techniques for obtaining estimates of deep percolation typically might involve the use of lysimeters or of micrometeorological techniques to measure evapotranspiration, neutron logging to measure soil-moisture-storage changes, and precipitation measurements to provide an estimate of infiltration. Such measurements generally would be impractical during a 1-year site investigation. However, water-balance modeling involving daily soil-moisture accounting for the root zones of the prevailing vegetation might be appropriate at most prospective repository sites.

Evaluation of the depth of penetration of such environmental tracers as ^{3}H or ^{36}Cl could be useful for evaluating recharge and proving or disproving the hypothesis of piston flow at a prospective repository site. The use of applied tracers might not be practical for a 1-year study but might be useful when linked with long-term monitoring.

Saturated-Zone Hydrology

The problems involved in evaluating the geohydrology of the saturated zone are radically different from those in evaluating the unsaturated zone. Both hydraulic head and the transport properties of the saturated media are relatively easily determined. However, the direction of flow, particularly the flow path of a given packet of water, may be difficult to determine, particularly in an nonhomogeneous or fractured aquifer system. Even in a fairly homogeneous aquifer, subtle bedding may markedly affect the flow path. Consequently, much of the emphasis on saturated-zone geohydrology needs to be placed on determining the geologic framework, the hydraulic-head distribution in three dimensions or at least within each permeable layer, and the aquifer-system boundaries.

Once the probable flow path through the saturated zone is delineated, estimates of flow velocity and effective porosity are needed. Commonly, calculations using Darcy's law might suffice, based on aquifer-test, digital-model-calibration, and laboratory-analysis (for fine-grained materials) values of hydraulic conductivity for the geohydrologic units. Effective porosity may be assumed to be equal to total porosity for unconsolidated deposits, but tracer tests or the evaluation of environmental tracers may be needed in fractured-rock environments.

Summary

In summary, flow and transport in both the unsaturated and saturated zones generally need to be evaluated at prospective repository sites. The main emphasis in evaluating the unsaturated zone generally needs to be in determining deep percolation or recharge and transport mechanisms. Emphasis in evaluating the saturated zone generally needs to be in defining the geohydrologic framework and probable flow paths from the prospective repository to points of ground-water discharge.

Burial of Low-Level Radioactive Waste in the Humid Northeastern United States

By David E. Prudic

Current practice in the United States is to bury low-level radioactive waste in shallow trenches in the unsaturated zone. The greater the thickness of the unsaturated zone the better. The vast majority of thick unsaturated zones occur in the more arid western States, particularly in the Basin and Range province of the Southwest where precipitation is minimal and depths to ground water commonly exceed 30 m. An example of shallow-land burial of low-level radioactive waste in the Basin and Range province is the repository site near Beatty, Nev., where average annual precipitation is less than 10 cm/yr and the unsaturated zone is about 85 m thick. The problem at this repository is to be able to measure any moisture at all.

In contrast, shallow-land burial in the humid northeast, where average annual precipitation generally exceeds 75 cm, has resulted in some migration away from the burial trenches to points of discharge. Such repository sites include those near Sheffield, Ill.; at the Oak Ridge National Laboratory, Tenn.; near West Valley, N.Y.; and at Maxey Flats, Ky. (fig. 1). The wastes at the sites near Sheffield and West Valley are buried in fine-grained glacial deposits, whereas the wastes at the Oak Ridge National Laboratory and at Maxey Flats are buried primarily in weathered zones of shale. The repository sites were selected to restrict the migration of radionuclides through the subsurface. However, the practice of filling shallow, long trenches with virtually uncompacted wastes in a variety of containers and then covering the wastes with a few meters of the excavated materials resulted in zones of permeable wastes and backfill being surrounded on three sides by less permeable rocks or deposits.

Radionuclide migration from the burial trenches resulted from infiltration of precipitation through the trench covers and caused a gradual filling of trenches with water until: (1) The water reached land surface; (2) the infiltrated water was able to seep outward from the trenches through fractures in the weathered zone or through fractures in consolidated rocks; or (3) the water percolated downward out of the trenches to more permeable underlying sediments. Continued monitoring and maintenance of these repository sites is necessary to assure minimal release of radionuclides to the environment; otherwise, locally harmful quantities of radionuclides might be released to the environment.

In general, many of the more populous States do not have propitious areas with thick unsaturated zones having minimal precipitation in which to bury the low-level radioactive waste generated in their jurisdiction. However, it may not be feasible to bury all the low-level radioactive waste in the more technically favorable sites in arid environments. Actually, several locales in the northeastern States might be suitable for the burial of low-level radioactive waste if burial practices are modified. An example of a possible locale is the present repository site near West Valley. There, shallow-land burial in a fine-grained till resulted in the gradual filling of the trenches with water until the water from two trenches overflowed to the land surface. Water subsequently was pumped from most of the burial trenches, treated, and released to a nearby creek. Additional till then was excavated nearby and placed over the burial trenches, but this may be only a temporary solution as the trenches may need continual maintenance to keep precipitation from entering them.

Although shallow-land burial of low-level radioactive waste has caused problems at the repository site near West Valley, the site could be used to test a concept described by Cherry and others (1979). Their concept is to place the low-level radioactive waste in saturated deposits below the zone of seasonal water-table fluctuations where the flow of ground water is minimal, and molecular diffusion is the dominant mechanism for migration of radionuclides away from the waste containers.

The fine-grained till at the repository site near West Valley seems ideal for testing this concept. The till is about 28 m thick at the shallow-land burial trenches and ranges from about 3 m thick 2 km south of the repository site to more than 35 m thick 1 km north of the site (Randall, 1980). The upper 3 to 5 m of the till is weathered and fractured, whereas below a depth of 5 m, the till generally is plastic and fracture free. Most of the precipitation that falls on the till either flows off as surface runoff, or as near-surface flow through a network of interconnecting mole runs or shallow cracks to nearby depressions, or is evapotranspired. The small proportion of precipitation that does infiltrate into the unweathered till flows predominantly downward at a rate (specific flux) of between 0.3 and 2.3 cm/yr (Prudic, 1986). The direction of flow in the unweathered till is controlled by partly unsaturated lacustrine deposit beneath the till (fig. 70), which function as a drain. Flow from the till into the lacustrine deposits is not enough to keep these deposits completely saturated. Saturated flow in the lacustrine deposits is laterally toward Buttermilk Creek where the small quantity of ground water that enters it seeps out along the bluffs or directly into the creek.

Burial of low-level radioactive waste beneath the weathered zone would greatly decrease the possibility of radionuclide migration along fractures; but large burial trenches (the length and width previously excavated, but deeper) are not feasible because the till at depth is too plastic. Exposed walls of large, deep trenches likely would collapse owing to the lack of support at depth. A viable alternative might be construction of large-diameter (2 to 5 m) auger holes with the waste buried at depths between 10 and 17 m below the land surface, as shown in figure 71. The cost of burying wastes in this way is more than for shallow burial, but the technique likely would decrease the future expense of continued maintenance of trench covers that must be done at the repository site.

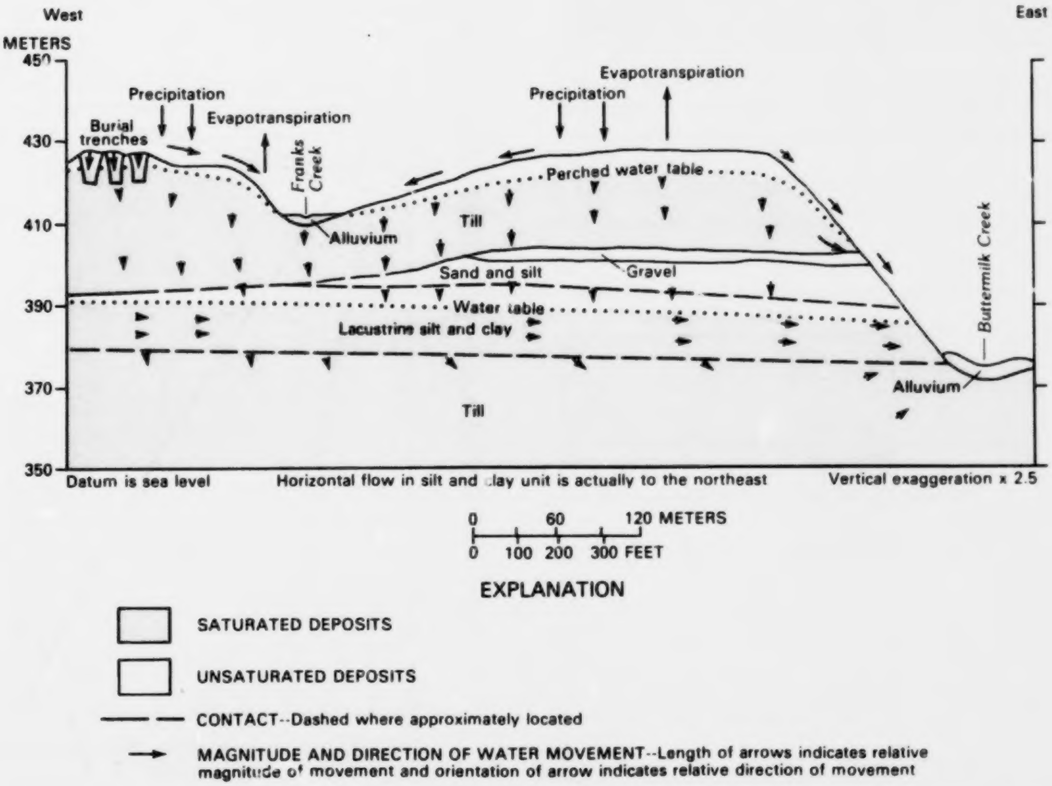
West
East
METERS
450
430
410
390
370
350
Precipitation
Evapotranspiration
Burial trenches
Franks Creek
Alluvium
Evapotranspiration
Precipitation
Perched water table
Till
Sand and silt
Gravel
Water table
Lacustrine silt and clay
Till
Alluvium
Buttermilk Creek
Datum is sea level
Horizontal flow in silt and clay unit is actually to the northeast
Vertical exaggeration x 2.5
0
60
120 METERS
0
100
200
300 FEET
EXPLANATION
SATURATED DEPOSITS
UNSATURATED DEPOSITS
CONTACT--Dashed where approximately located
MAGNITUDE AND DIRECTION OF WATER MOVEMENT--Length of arrows indicates relative magnitude of movement and orientation of arrow indicates relative direction of movement

Figure 70. Lithology and saturation of units, and relative magnitude and direction of water movement at the low-level radioactive-waste repository site near West Valley, N.Y. (modified from Prudic, 1986, fig. 9). Direction of flow in the till is controlled by partly unsaturated lacustrine deposits beneath the till. Saturated flow in the lacustrine deposits is laterally toward Buttermilk Creek.

Some of the auger holes could penetrate discontinuous lenses of silt, sand, and, less commonly, gravel beneath the weathered zone that may cause water to enter the holes or allow more rapid radionuclide migration. At the repository site near West Valley, the lenses are small in areal extent and surrounded by the much finer grained till that ultimately controls radionuclide migration to points of discharge.

The concept is feasible only if the permeability of the materials is such that molecular diffusion is the dominant mechanism by which radionuclides can migrate. On the basis of studies at the repository site near West Valley, ground-water velocities through the till are less than 6 cm/yr and result in diffusion controlling radionuclide migration (Prudic, 1986). Radionuclide analyses of till samples collected beneath three burial trenches indicate that detectable concentrations of ^{3}H had migrated less than 3 m in 7 to 11 years since the time the waste was buried to the time the samples were collected. Assuming a constant ^{3}H concentration of 1.44 μCi/mL in burial-trench water for 100 years, a constant water level in the burial trench for 100 years, a porosity θ of 0.3, a specific flux (q) of 0.7 cm/yr, a tortuosity factor τ of 1.6, a diffusion coefficient (D_d) of water 475 cm^2/yr, and a distribution coefficient (K_d) of 0.0 mL/g, detectable concentrations of ^{3}H are projected to migrate only about 10 m beneath the trenches after 100 years (fig. 72). Projecting beyond 100 years is unreasonable because radioactive decay of ^{3}H in the waste probably will result in much smaller ^{3}H concentrations in the burial-trench water.

Most of the other radionuclides will migrate at a much slower rate than ^{3}H because of ion exchange with the clay minerals in the till (primarily illite) and because some of the pores may be too small for the larger radionuclides to pass through pores. Mercury-porosimeter tests of seven unweathered till samples indicate that 95 percent of the pore openings are less than 1 μm whereas about 30 percent of the pore openings are less than 0.1 μm (fig. 73) (Prudic, 1982). An example of the pore sizes in the unweathered till is shown in figure 74, which is a photomicrograph of an unweathered till sample as viewed through a scanning-electron microscope.

Carbon-14 is one radionuclide that might migrate from the deeply buried low-level radioactive waste. This migration may be either to the land surface or through the till and lacustrine deposits to Buttermilk Creek because ^{14}C is not likely to exchange with the clay in the till because it is a common radionuclide of the waste and because it has a long half-life (5,730 years). Detectable concentrations of ^{14}C are projected to migrate through the till beneath the present burial trenches to the underlying lacustrine deposits in about 1,500 to 20,000 years (Prudic, 1986). This projection does not include slow

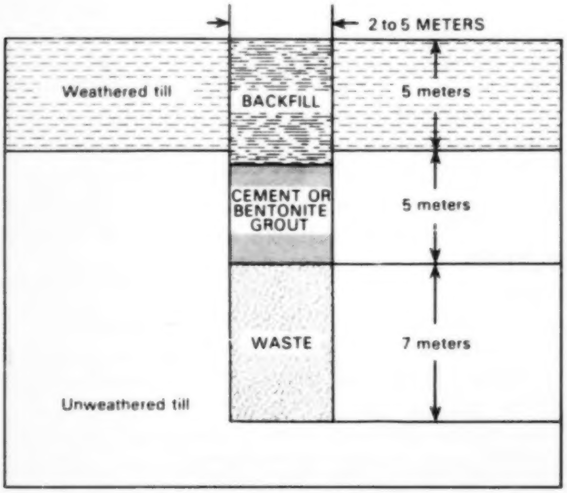

Figure 71. A possible method of burying low-level radioactive waste in a fine-grained till at the repository site near West Valley, N.Y. (method modified from Cherry and others, 1979, fig. 2).

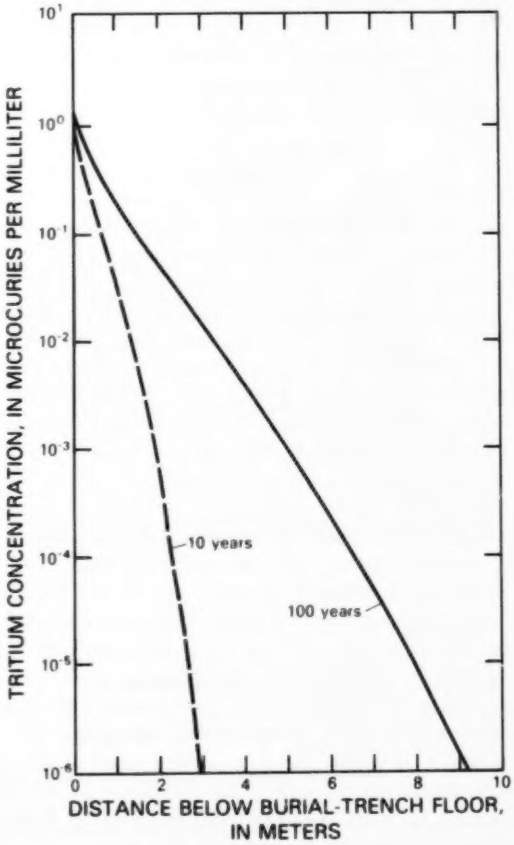

Figure 72. Predicted tritium concentrations in water beneath burial trench 5 after 10 and 100 years, low-level radioactive-waste repository site near West Valley, N.Y. (modified from Prudic, 1986, fig. 33).

lateral migration through the lacustrine deposits to Buttermilk Creek. It seems possible that detectable concentrations of ^{14}C could slowly reach the land surface even if the waste is buried deeply in the till, but at rates much less than that which is being released as gases through the covers at the present burial trenches.

In conclusion, the low-level radioactive-waste repository site near West Valley perhaps could be used experimentally to bury low-level radioactive waste in a manner considerably different and initially more expensive than the current (1987) practice of shallow-land burial. The concept of deeper burial in the saturated zone also may be feasible in other slightly permeable sediments in the northeastern United States if a site could be located at the beginning of a long flow path in which flow rates are slow.

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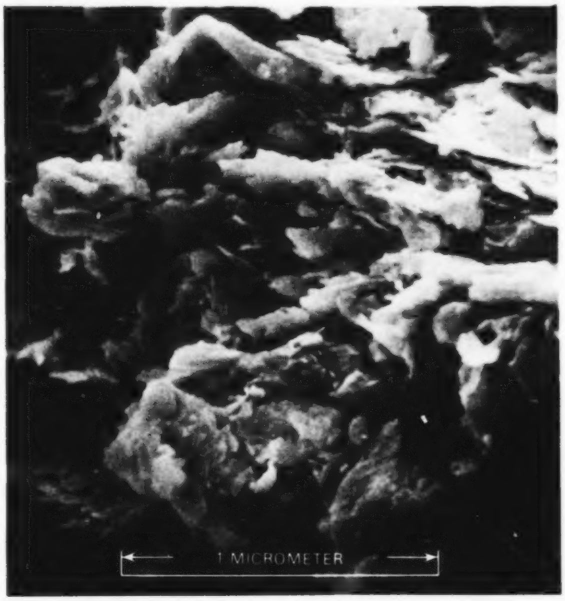

Figure 74. Photomicrograph of an unweathered till sample collected at the low-level radioactive-waste repository site near West Valley, N.Y. Vertical section magnified 4,675 times.

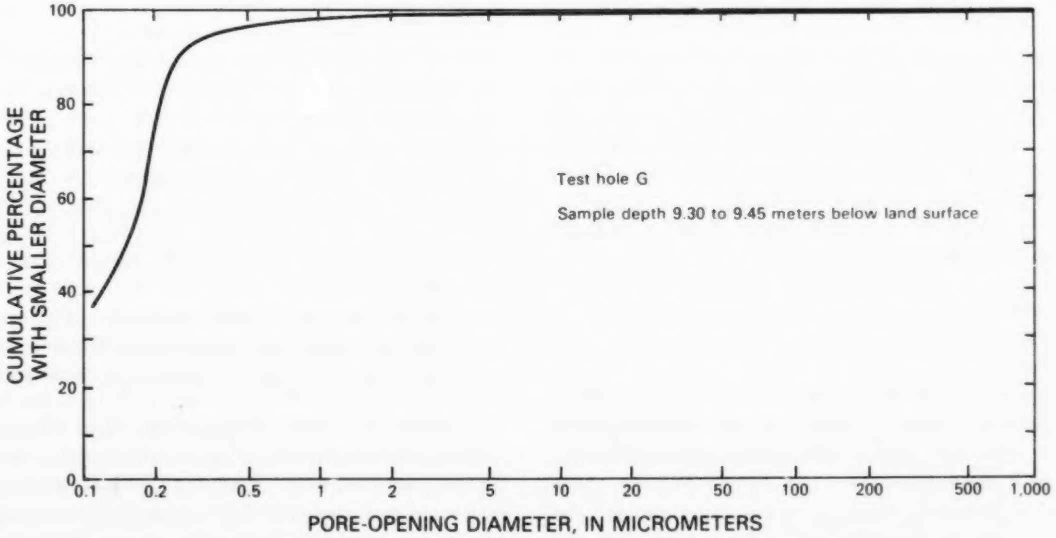

Figure 73. Cumulative percentage of pore-opening diameters of a till sample from test hole G at the low-level radioactive-waste repository site near West Valley, N.Y. (modified from Prudic, 1982, fig. 7).

Chemical Modeling of Regional Aquifer Systems—Implications for Chemical Modeling of Low-Level Radioactive-Waste Repository Sites

By Donald C. Thorstenson

Modeling chemical reactions in natural systems might arbitrarily be divided into two areas: (1) Modeling of major reactions that control the water chemistry, including pH, alkalinity, solute concentrations, redox conditions, and so forth; and (2) modeling of minor reactions that are controlled or affected by water chemistry, including speciation and sorption of minor and trace elements, and so forth. Most reactions of regulatory concern are possibly minor reactions by these definitions; however, modeling the minor reactions implies a knowledge, or models, of the major reactions. The fundamental principles are the same for both. The goal of this modeling approach is simply to identify the major reactions occurring in the system; the interactive use of these models with hydrologic models can provide much useful information pertaining to the nature of flow systems. These chemical-reaction models are not solute-transport models.

This discussion is based largely on selected studies related to or derived from the U.S. Geological Survey's Regional Aquifer Systems Analysis Program. One modeling study will be discussed in some detail; a few pertinent comments will be made on others. The modeling of these large-scale systems assumes that the aquifers integrate local hydrochemical heterogeneity into regional homogeneity, providing the basis for the concept that a relatively small number of reactions can, in fact, model the major chemical changes in these systems. Three aspects of these regional modeling studies will be briefly addressed: (1) The data required for the modeling, (2) the assumptions involved in the model, and (3) the uniqueness of the resulting model. Once these three factors have been examined, the questions to be addressed pertain to the need for, or the applicability of, these modeling techniques to the smaller-scale studies that form the basis for this workshop.

The modeling approach used is based on the deceptively simple equation:

$$\text{Initial-Water Composition} + \text{“Reactant Phases”} = \rightarrow \text{Final-Water Composition} + \text{“Product Phases.”} \qquad (1)$$

The initial- and final-water compositions are assumed to be known at two points along a flow path. Therefore, the modeling exercise consists of identifying, subject to thermodynamic and other constraints, the nature and quantity of: (1) Reactant phases—constituents entering the aqueous phase, such as minerals or gases dissolving; and (2) product phases—constituents leaving the aqueous phase, such as minerals precipitating or gases exsolving. Mixing problems can be treated by defining a water of known composition as a reactant or product phase as needed. For details of the modeling approach, see Parkhurst and others (1980), Parkhurst and others (1982), Plummer and others (1983), and Plummer (1984).

In the examples discussed below, some assumptions are common to all: (1) The flow directions are known or inferred ("initial" and "final" are defined as occurring along a flow path); (2) hydrodynamic dispersion is negligible; and (3) the major-ion composition, pH, and, as completely as possible, redox characteristics are known for the initial and final water compositions in order to permit aqueous-speciation calculations. The modeling exercise consists of: (1) Choosing a set of "plausible phases," such as minerals, gases, organic material, or other constituents that can realistically be expected as reactants or products in a given aquifer system; (2) using an inverse-problem approach to force a model to fit the actual water chemistry via mass-balance equations for chemical elements, electrons, and isotopes derived from equation 1; and (3) testing that model for thermodynamic validity and consistency with any other available hydrochemical data. The number of plausible phases almost invariably exceeds the number of mass-balance constraints; the resulting models, thus, are nonunique.

The Floridian Aquifer

The following discussion is exclusively from Plummer and others (1983). Available data include the following:

1. Aqueous phase—Concentrations of major ions and values of pH; concentrations of Fe and H_2S; $\delta^{34}S$ for dissolved sulfide and sulfate; $\delta^{13}C$ and ^{14}C, in percent modern carbon, for dissolved inorganic carbon species.
2. Solid phases from known mineralogy—gypsum ($CaSO_4 \cdot 2H_2O$); calcite ($CaCO_3$ to $Ca_{0.98}Mg_{0.02}CO_3$); magnesium calcite ($Ca_{0.95}Mg_{0.05}CO_3$); dolomite [$CaMg(CO_3)_2$ to $Ca_{1.05}Mg_{0.90}Fe_{0.05}(CO_3)_2$]; ferric hydroxide (FeOOH); iron sulfides (FeS_2, FeS).
3. Assumptions—The aquifer system is closed to CO_2, and sources of reduced carbon occur at valence zero, that is, "CH_2O", and CH_4 at valence –4.

Given the above information, all of which is well justified based on knowledge of the system, six mass-balance models were constructed that simulated the major-ion water composition along the flow path; only one of the six was determined to violate thermodynamic constraints by requiring precipitation of large quantities of gypsum from undersaturated solutions. Thus, even when the major-ion water chemistry and aquifer mineralogy are known in considerable detail, five available mass-balance models remain consistent with known data and would be considered valid in the absence of other data.

The sulfur-isotope data provide a link between the carbon and sulfur sources into the aqueous phase via sulfate reduction. When the sulfur-isotope data are added as a constraint, all five of the remaining mass-balance models are invalidated. A new set of six mass-balance models were generated by adding CO_2 as a "plausible phase" and adding a sulfur-isotope equation to the set of mass-balance constraints. All six of these new mass-balance models fit the chemical and the sulfur-isotope data; all require the input of CO_2. When the $\delta^{13}C$ data are considered, one of the six mass-balance models is eliminated. Thermodynamic constraints make questionable, but do not rigorously eliminate, four more of the mass-balance models. The remaining mass-balance model (Plummer and others, 1983, p. 679) is in mmol/Kg H_2O:

$$\text{Initial water} + 0.96\ CaMg(CO_3)_2 + 1.68\ CaSO_4 \cdot 2H_2O + 0.17\ CH_2O + 0.53\ CO_2 + 0.03\ FeOOH \rightarrow 1.84\ CaCO_3 + 0.03\ FeS_2 + \text{Final water.} \qquad (2)$$

When the ^{14}C concentration in the water is considered, if the incoming CO_2 is assumed to be 50 percent modern, a ground-water velocity of about 9 m/yr is estimated. This velocity is almost identical to estimates of ground-water velocity obtained from hydrologic models.

Of particular importance here is examination of the changes in the nature of the reaction mass-balance models as a function of the type of data available for modeling.

1. With abundant mineralogic data and complete major-ion data for the water, five of six mass-balance models were determined to match all data, based on the hydrologic assumption that the system was closed to CO_2. In the absence of additional data, it could be argued that any one of these models might have been "the model" for this system, never questioning the assumption of the closed system.
2. The "addition" of the sulfur isotope data and the constraints such an addition imposes on the sulfate-reduction process indicates mass-balance models that all require input of CO_2 and, therefore, the assumption is made that the aquifer is at least partially open to a CO_2 source. Thus, the acceptance or rejection of a significant hydrologic hypothesis depends entirely on the presence or absence of chemical data, in this case data for sulfur isotopes.
3. Ground-water velocity can be calculated based on an assumed ^{14}C content of the incoming CO_2. The calculated velocity in this example is relatively insensitive to this assumption (Plummer and others, 1983, table 9), but this insensitivity is due in large part to the fact that the quantity of CO_2 entering the system is small relative to the total dissolved CO_2 present in the "initial water." Were this not the case, the measured distribution of ^{14}C in the aquifer might force consideration of still other hydrologic hypotheses.

It needs to be reemphasized that, although wells in the above example are tens of kilometers apart, the same principles apply for wells that are 10 m apart. The fact that conceptual hydrologic models, as well as chemical models, may depend on the nature of the chemical data available needs to be recognized. This point is exceptionally well made in a paper by Plummer (1984). Plummer (1984) provides an extensive discussion of the philosophy of the modeling approach described above, an evaluation of the forward approach versus the inverse approach to geochemical modeling, and a detailed example from a part of the Madison aquifer in the Mississippian Madison Limestone in Wyoming and Montana. The forward approach results in a predictive model, based on initial conditions and assumed mineralogic and thermodynamic constraints, that is used to attempt to obtain simulated data nearly identical to the measured data. Forward-approach calculations are not constrained by definition to exactly match the analytical data, as are inverse-approach calculations. In this author's opinion, Plummer (1984) needs to be read by anyone considering chemical modeling as it relates to characterization of low-level radioactive-waste repository sites.

The Madison Aquifer

Another intensively studied regional carbonate aquifer is the Madison aquifer in the Black Hills and associated areas in Wyoming, Montana, and South Dakota (Back and others, 1983; Busby and others, 1983; Back and others, 1985; Konikow, 1985; Busby and others, in press). Data available include mineralogy that is detailed in some areas, minimal in others; $\delta^{34}S$ for gypsum/anhydrite; $\delta^{13}C$ for carbonate minerals; and detailed water chemistry, including major ions, pH, $\delta^{13}C$ and ^{14}C, in percent modern carbon, for dissolved inorganic carbon species, and $\delta^{34}S$ for dissolved sulfide and sulfate. Chemical modeling along several flow paths (Busby and others, in press) indicates dissolution of gypsum/anhydrite and dolomite, calcite precipitation, and locally important sulfate reduction, halite dissolution, and exchange of Ca^{2+} and Mg^{2+} for Na^+. The flow-rate estimates and mass-transfer calculations indicate that most reaction occurs downgradient rather than in the recharge area, which is unusual. Important assumptions include: (1) Carbon at valence zero, that is

"CH_2O", in sulfate reduction; and (2) the existence of the (Ca^{2+} + Mg^{2+}) for Na^+ exchange reaction that is inferred from modeling the water chemistry, but for which there is no direct mineralogical evidence.

Coastal-Plain Aquifers

A similar modeling effort in aquifers dominated by aluminosilicate reactions has been completed by Lee (1985) for coastal-plain aquifers of Mississippi and Alabama. Available data include general mineralogy from cores, but, as pointed out by Lee (1985), not in sufficient detail to truly document the modeled reactions. Data for the aqueous phase consist of: pH, major ions, plus dissolved Al, Fe, H_2S, N_2, O_2, Ar, and CH_4; and $\delta^{13}C$ for the dissolved inorganic carbon species. The resulting models indicate reactions dominated by feldspar dissolution near the recharge area, further dissolution of feldspar and amorphous aluminosilicate downgradient with associated precipitation of sodium-bearing clay minerals, and substantial Ca^{2+} for Na^+ exchange. Minor sulfate reduction and methanogenesis also are indicated, as are substantial CO_2 from lignitic carbon in the aquifer. Major assumptions include: the composition of the aluminosilicate phases; net valence of reactive carbon of zero, "CH_2O," $\delta^{13}C$ of CH_2O; and the occurrence of Ca^{2+} for Na^+ exchange. Lee (1985) determined that, even within these assumptions, variability in the model results was dependent on the initial quantity of dissolved CO_2 assumed to be present in water recharging from the unsaturated zone.

Sorption and ion-exchange reactions are a major concern in characterizing low-level radioactive-waste repository sites. It is, thus, of some interest to consider the exchange of Ca^{2+} for Na^+ on exchange sites in aquifer-matrix materials, a process thought to be responsible for the formation of enriched sodium bicarbonate waters in many regional aquifers and postulated as a "plausible reaction" in all of the preceding regional models except the Floridan aquifer. This process, which was discussed extensively in a classic paper by Foster (1950), formed the basis of a substantial exercise in "forward" modeling, with discussions as to the nonuniqueness of the models by Thorstenson and others (1979). However, to the author's knowledge, conclusive documentation of Ca^{2+} for Na^+ exchange, as opposed to silicate hydrolysis and attendant secondary-mineral precipitation, was not achieved on a regional scale until Chapelle (1983) and Chapelle and Knobel (1983, 1985) worked on the Aquia Formation of Paleocene age in Maryland. These investigators' success was due to determining the chemistry of exchange sites on the aquifer matrix, made possible in part by the mineralogic simplicity of the Aquia aquifer. On a local scale, evidence of Ca^{2+} for Na^+ exchange on lignite has been documented, again through solid-phase analysis, by Fisher and others (1985). The point to be made is that although exchange of Ca^{2+} for Na^+ has been postulated as an important, or dominant, reaction in many regional systems, conclusive evidence for its occurrence is only now appearing. Even in those systems where exchangeable-cation data document this reaction, the source of CO_2 required to maintain the measured pH values during the exchange reaction remains problematic.

The point has been emphasized that the net valence of organic carbon in the preceding examples has been assumed, not known. This is particularly pertinent to this workshop in that most, if not all, low-level radioactive-waste repository sites will contain abundant organic material. This poses two types of problems—those specific to the organic material, such as potential chelating effects of specific compounds, toxicity, and so forth, and an infinitely variable net oxidation state of reactive organic carbon depending on redox conditions in the burial trenches, microbial degradation along ground-water flow paths, and so forth. The latter problem is compounded by the lack of fixed stoichiometry of the organic phase(s) and the lack of previous knowledge of the relative rates and reaction stoichiometries for degradation of specific organic compounds. These considerations add a major complexity to modeling the major reactions because the net valence of the reactive carbon can range from –4 to +4. Note that the modeling conclusion of the Floridan aquifer being open to CO, in essence, stipulates that the net valence of "reactant" carbon is consistent with the sulfur-isotope data.

The art of mass-balance modeling applied to organic compounds is in its infancy; the only paper to the author's knowledge that attempts this is a study of the Army Creek Landfill, Delaware, by Baedecker and Apgar (1984); see also Baedecker and Back (1979). The study of the Army Creek Landfill included general mineralogy, aqueous chemistry, and isotope data, including a number of specific organic compounds and a variety of redox-active species not generally considered in mass-balance modeling. Major conclusions from this study are that large quantities of organic matter are fermented between the landfill and the first recovery well, and that the redox zones detected in the plume are controlled by competing rates of reaction and hydrologic transport. Discussion also is presented regarding the nonunique aspects of the models.

An exhaustive analysis of the nonuniqueness problem is provided by Robertson (in press), who used several hundred combinations of mass-balance models in an attempt to define reactions governing the geochemistry of water in about 70 alluvial basins, primarily in Arizona. Robertson's (in press) work included extremely diverse geographic, hydrologic, geologic, and geochemical systems. It is particularly encouraging that, on the basis of the available mineralogic and geochemical data and reasonable assumptions, only about 20 reactions are likely geochemical processes, and that, in flow systems for which sufficient mineralogic and hydrochemical data are present, the major geochemical features are accounted for.

What conclusions can be drawn from this presentation that are relative to the problem of characterization of low-level radioactive-waste repository sites? Plummer and others (1983) concluded that, in a general way, the value of the mass-balance calculations is directly proportional to the quantity of analytical data available. The value of the reaction-path calculations tends to be greater in situations where fewer data are available and a greater hypothetical element is present in the modeling process—a conclusion reinforced and expanded on by Plummer (1984). It seems reasonable that for repository-site characterization, the hypothetical element needs to be minimized, the quantity of analytical data available maximized, and, thus, for the major geochemical reactions at potential repository sites, the modeling method of choice is the mass-balance method. It also needs to be recognized that none of the above modeling efforts have produced a completely definitive model, in spite of large expenditures of time, effort, and dollars. If there is a generalization to be made, it is that models based solely on aqueous geochemistry are nonunique. The degree to which this nonuniqueness can be made to approach uniqueness will depend on the degree to which both the water chemistry and the chemistry of nonaqueous phases at potential repository sites can be characterized.

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Test Drilling, Sampling Procedures, and Monitoring Installations for Characterization of a Low-Level Radioactive-Waste Site

By Warren E. Teasdale

Prior to disposing of low-level wastes in a waste-repository site, the ambient geohydrologic conditions of the prospective area needs to be determined as accurately as possible to ensure that it is a suitable location for waste-isolation purposes. A few of the more practical drilling methods and sampling techniques for determining these conditions are discussed in this paper. The procedures mentioned pertain to relatively shallow drilling and sampling depths in unconsolidated materials. Unfortunately, these types of materials are the most difficult from which to obtain undisturbed core samples and in which to complete representative monitoring wells and test holes.

The installation of monitoring wells needs to be accomplished using the most suitable materials available for the construction and completion of the wells. Considerations include: (1) The reactivity of the casing composition to the proposed waste contaminants, (2) diameter of the well for its specific purpose, (3) well-screen design, and (4) well completion and development procedures. Likewise, the drilling and sampling methods selected for evaluation of the potential site need to be chosen to provide the optimum core and log data for the particular geohydrologic environment to be encountered.

The purpose of this paper is to assist those persons concerned with establishing drilling programs for collecting useful subsurface geohydrologic data by providing brief descriptions of a few of the more practical drilling and sampling techniques for obtaining meaningful information in unconsolidated materials. Also, there are some basic considerations that need addressing before a drilling program is initiated. Briefly, these include, but are not restricted to: (1) Type of materials to be drilled and sampled; (2) accessibility of drilling site; (3) anticipated total depth of completed wells and test holes; (4) casing diameter selection to accommodate well use; (5) quality of drilling samples required; (6) potential for cross-contamination occurrence during drilling, a condition more likely to occur on a contaminated site; (7) ease of cleaning equipment after drilling at a contaminated site; (8) ease of gravel packing or grout installation; (9) availability of in-house or contractor-supplied equipment; (10) cost; and (11) time available to complete the investigation. Prior decisions made on these items will allow the drilling and other field personnel to make better preparations logistically and to make proper equipment selections (Morrison, 1983) to carry out the project without having future operational misunderstandings as the field program progresses.

Drilling Methods

Auger drilling offers an excellent method for collecting subsurface data from shallow unconsolidated materials and relatively soft rocks. Soil profiles can be determined, and disturbed soil samples of the penetrated materials can be collected for visual analyses from sample returns of the auger-drilled sediments. It is a dry-drilling method; that is, drilling usually is accomplished without using air, water, or any other media to flush the hole. Cuttings are lifted out of the hole and deposited at the surface by the augering action.

Two basic types of continuous-flight augers are used for auger drilling. They are the solid-stem type and the hollow-stem type. In general, preliminary reconnaissance-exploration drilling of the potential waste repository site can be done with solid-stem augers. They are more convenient to use, less complex, faster, and easier to handle than larger hollow-stem augers. The presence and extent of confining beds, sand and gravel lenses, ground-water levels, and basic site-profile data of the lithology can be mapped on the basis of the auger-drilled sections. Contingent on the results of the initial investigation and the information obtained, it might be desirable to conduct more extensive testing and more detailed soil sampling of selective areas in order to understand better the geohydrology. It is recommended that hollow-stem augers and drive-sampling apparatus be used for more detailed studies.

Hollow-stem augers are used to drill and case the hole simultaneously, thereby eliminating hole-caving problems and contamination of soil samples. Also, monitoring-well casing, geophysical-logging probes, aquifer-testing equipment, and water or soil-sampling devices can be installed directly through the hollow-stem augers.

Although it is one of the best methods for collecting uncontaminated representative samples, auger drilling has its limitations, particularly the hollow-stem technique. Auger drilling, as previously mentioned, is a method that is limited to the drilling of unconsolidated materials or relatively soft rocks. Depending on the nature of the sediments penetrated, auger-drilled depths seldom exceed several hundred feet. Other limiting factors include the rig size, auger diameters, and most important, operator experience and expertise. Additional information on auger drilling and sampling methods is provided by Shuter and Teasdale (1989).

The cable-tool percussion method of drilling, one of the oldest drilling methods known, is still a versatile tool for obtaining reliable subsurface geohydrologic information. Evaluation of the bailer cuttings in conjunction with a competent cable-tool drillers' log provides a good description of the materials penetrated. When drilling unconsolidated sediments, casing is driven as the hole progresses to support the hole wall and prevent caving (Campbell and Lehr, 1973). Water, sometimes with a drilling mud, usually is poured in the hole when drilling dry materials above a saturated zone. This enables the cuttings generated by the bit action to form a slurry and remain in suspension for ease of periodic bailing out of the hole. The cuttings can be bailed out at any specified interval during the drilling process for inspection and lithologic logging. Driller competency must be heavily relied upon, however, when interpreting lithology from a bailed-out section of the hole. What appears to be a dirty sand might actually have been a layer of gravel and a clay or silty-clay lens. The bailer sample is a ground-up mixture of these materials and without a reliable driller's log, an erroneous lithologic log will result.

Drive-core samples of either dry or saturated materials also can be taken with a cable-tool rig. After first bailing the drilled cuttings out of the hole, a drive-core sampler is affixed to the tool joint below the drill jars using an appropriate crossover sub (fig. 75). The sampler then is lowered to the bottom of the hole and driven to the desired depth by alternately lifting and dropping the drill jars. This technique is contrary to the normal use of the drill jars; but, if driving and retrieving of the sampler is done carefully, no damage will be done either to the drill jars or the sampler. This sampling method provides a representative sample of the material and not a mixture of the sediments drilled (Shuter and Teasdale, 1989).

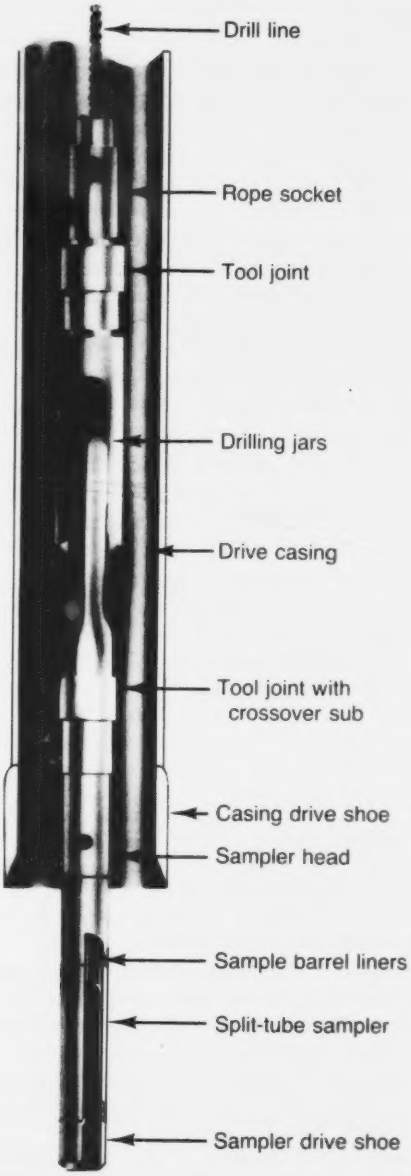

Figure 75. Cable-tool drill with drive-sampling apparatus.

In drilling unconsolidated sediments, the hydraulic-rotary method is faster and usually a more economical method than the cable-tool percussion method. Hydraulic-rotary drilling is accomplished by circulating a drilling fluid through the bit while rotating and lowering the string of drill pipe. In general, there are three basic types of drilling fluids and these are: (1) Water, with the addition of either native clays or with commercial, high-yield bentonites, that is, a bentonite that will yield a specific viscosity to the largest volume of water; (2) mud-laden, oil-base mixtures; and (3) air. Oil-base muds usually have no application in ground-water investigations.

The purpose of the drilling fluid is to: (1) Remove the drilled cuttings from the hole; (2) cool and lubricate the bit; (3) support and prevent caving of the borehole wall; (4) build a filter cake or rind on the borehole wall preventing fluid loss in, and limiting mud invasion of, the drilled sediments; (5) control formation pressures; and (6) lubricate the drill pipe in the hole. Mud control is extremely important to the proper collection of samples and is of great significance in mud-rotary coring applications.

Plain water, having a Marsh-funnel viscosity of 26 s, or other thin drilling-fluid mixtures cannot be used when coring unconsolidated sediments. Whenever unconsolidated materials are cored, it is necessary to quickly form a thin filter cake on the borehole wall, as well as on the exterior of the core as it is being cut so that little or no filtrate invasion or erosion of the core occurs. The viscosity of the drilling fluid must be kept high; but the mud weight must be kept low. For example, when coring sands, the drilling-fluid viscosity should range from 50 s to perhaps greater than 100 s, with 75 s being the average. The drilling-fluid weight should not exceed about 1.05 to 1.08 kg/L, including the cuttings weight. These viscosity and weight restrictions on the drilling fluid are necessary to obtain uncontaminated core from unconsolidated formations. Low-solid polymers also can be added to the bentonite drilling-fluid mixture to increase the viscosity. If added drilling-fluid weight is required to keep the borehole from caving, it should be accomplished by adding barite or similar drilling-fluid weight additive and not simply by letting the sand and cuttings content of the fluid build to a high level.

Coring bits used for coring of unconsolidated materials are of the recessed, bottom-discharge types. Because of the recessed configuration of the waterways, the drilling fluid does not come in direct contact with the core, thereby practically eliminating core-erosion problems. Another advantageous feature of this type of coring bit is that the fluid tends to be thrown outward, not downward, as the drill pipe rotates, further preventing washing and contamination of the core.

The penetration rate, fluid pressure, and the rotational speed of the drill pipe are all important variables to be considered when coring unconsolidated sediments. Even though the drilled materials are unconsolidated, they must be cut as they are cored and not merely pushed into the core barrel. Again, the drillers' experience and expertise play a vital role in the coring operation.

Casing and Well Installation

Once the borehole has been drilled, cored, and lithologically sampled to the desired depth and it has been drilled to a sufficient diameter to accept the selected screen and casing, it is ready to be completed as a monitoring well. If it has not, the hole must first be reamed using a larger reaming bit before the well installation can be accomplished.

If the borehole has been drilled by a method other than by auger drilling, and a drilling fluid has been used, the following is done to condition the hole for casing and well-screen installation. The drill pipe is lowered to within about 6 in. of the bottom of the borehole and circulation of the drilling fluid is continued at a low to moderate rate (10 to 30 gpm) until the cuttings are flushed from the hole. Care must be taken while circulating so as not to erode the borehole excessively or damage the filter cake causing hole collapse.

When it appears that most all of the drill cuttings have been removed, a final flushing of a mud-rotary drilled hole using a freshly prepared, low-viscosity drilling mud (about 35 s) is advisable. This procedure will remove most of the sand-sized cuttings still remaining in suspension in the drilling fluid and allow these fine particles to settle out in the mud pit instead of settling to the bottom of the hole.

After flushing, the string of drill pipe is removed from the hole at a relatively slow rate using a vented hoisting plug. This technique minimizes differences in hydrostatic head between the formation and the hole by allowing a completely unrestricted movement of fluid out of the drill pipe and bit. If the drill pipe is pulled fast without using a vented hoisting plug (referred to as dry pulling), bit-swabbing damage to the hole will occur necessitating extensive flushing and redrilling to get back into the hole.

If open-hole geophysical logging or sampling methods are to be used requiring no damage or bridging of the hole during removal of the drill pipe, drilling fluid should be circulated during removal of drill pipe (Keys and MacCary, 1971). This guarantees that no great differential pressures will develop between the formation and the borehole; also, circulation will prevent buildup of muds and sands on the bit that make it act like a swab.

After the hole has been flushed and the drill pipe removed, the well screen and casing are set. If the hole contains drilling fluid, it is pumped out and the well is developed using appropriate well-development techniques to remove the introduced fines, to loosen or redistribute compacted granular materials, and to remove some of the normal fines of the aquifer materials surrounding the borehole.

Summary

The characterization and monitoring of a low-level waste-repository site in shallow, unconsolidated materials require the geohydrologic conditions and parameters of the prospective area be as accurately determined under ambient conditions as is possible. In order that much of this information be ascertained, holes must be drilled; lithologic samples and cores must be taken; and monitoring wells must be installed, developed, and completed in selected boreholes. Some suggested drilling methods and sampling or coring techniques as applied to unconsolidated sediments include: (1) Solid- and hollow-stem auger drilling and sampling, (2) cable-tool percussion drilling and sampling, and (3) hydraulic-rotary drilling and sampling.

After the hole has been drilled and sampled to the desired depth, it must be flushed of all drilled cuttings and conditioned. Following conditioning, open-hole geophysical logging can be run and the well screen and casing installed according to the required specifications for the intent of the well. To ensure that the screen is not plugged and the completed well is responsive to the aquifer, appropriate well-development techniques are then applied (Driscoll, 1986).

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Borehole Geophysical Methods Applicable to Characterization of a Low-Level Radioactive-Waste Site

By Frederick L. Paillet

Geophysical well logs will be an important factor in radioactive-waste disposal studies in the future, including site characterization, determination of site parameters for model studies, and monitoring performance of established disposal sites. The single most important aspect of well logs in initial site characterization is the continuous profile of geological properties provided by the log. These profiles provide means whereby limited and time-consuming tests performed on a finite number of samples may be placed in geological context. The most important concern in comparing logs to core data is the relatively large sample volume of the logging tool in comparison to the size of core samples used for testing. Site characterization efforts usually require that a sufficient number of core tests be run to ensure a statistically meaningful correlation between core data and log values. Correlations establishing possible depth corrections, along with correlations between geotechnical parameters measured directly on core and geophysical log measurements, such as gamma activity and electrical resistivity, probably are the single most important step in geophysical logging for quantitative model parameters at radioactive-waste sites.

Well-log applications for characterization and post-disposal monitoring at low-level radioactive-waste disposal sites can be divided into several distinct phases: (1) Lithology profiling, (2) determination of physical and hydraulic properties of geological units, and (3) sampling quality of ground water prior to site development. The first phase, lithology profiling, involves most standard applications of geophysical logs in hydrogeology. One of the most important concerns is maximizing vertical resolution in shallow boreholes. Sample volume size is related to tool configuration, but successful logging with small sample volumes requires minimization of borehole effects because the disturbed borehole region occupies a much larger percentage of a reduced sample volume. The second phase, determination of properties, involves many existing methods for determination of mechanical and geochemical properties of sediments. However, successful site models will require greatly improved resolution. Until calibration methods are improved, accurate determination of formation properties will rely on careful correlations between results of geologic tests on core samples and well-log data. The third phase, water-quality sampling, uses geophysical logs as a means of relating properties of water samples from discrete depths to the continuous profile of water quality within sediments.

The emphasis on improved vertical resolution and highly accurate estimations of formation properties increases the significance of borehole conditions and drilling disturbance in the vicinity of the borehole. Recent studies show that drilling method greatly affects the character of well logs through the extent of drilling-induced disturbance. Improved log analysis techniques for the recognition of drilling-induced disturbance will be an important element in geophysical research for radioactive applications.

Water-quality estimates from geophysical logs at potential low-level radioactive-waste disposal sites will be especially difficult. Several established techniques for such determinations exist, but all require significant contrast between solute content of drilling mud and formation waters, open borehole, and low clay-mineral content. The most advanced induction logging equipment shows some promise of measuring electrical conductivity in clay-rich formations behind casing, but the presence of electrically conductive clay minerals greatly complicates the interpretation of water quality. Several geophysical logs now can provide useful indications of changed conditions at established waste-disposal areas. These include natural gamma logs to indicate increased manmade radioisotope activity, neutron logs to detect changes in saturation or compaction, and electrical induction logs to determine changes in solute content in ground water.

One of the most important problems in site characterization is the detection of fractures or small sand lenses that may act as conduits in otherwise nearly impermeable, geochemically retarding formations. These conduits are difficult to sample in drilling and are not readily detected by geophysical logs. The most reliable geophysical indicators of fractures, acoustic and electrical resistivity logs, do not work well in shallow, unconsolidated materials or cased boreholes. The acoustic televiewer, because it is a reliable indicator, will continue to be an important tool in fracture identification (figs. 76 and 77). Future research will concentrate on improved televiewer logs in shallow, poorly consolidated materials (Paillet and others, 1985; Paillet, 1985).

Several recent advances in geophysical logging appear to have important applications in radioactive-waste disposal. These include improved methods for acoustic log interpretation in low strength, clay-rich sediments; high-frequency "complex" resistivity logging; and gamma spectral/neutron activation logging. Recent methods in acoustic full-wave logging show that the mechanical properties of poorly consolidated materials can be determined using lower source frequencies and inversion of data from arrays of multiple receivers (Cheng and Toksoz, 1983; Hornby and Murphy, 1987). Some of these methods appear to work in cased boreholes. Complex resistivity logging appears to provide a means for separating conductivities produced by solutes in ground water and clay minerals present in the formation (Shen, 1985). The approach works by the simultaneous measurement of electrical conductivity and dielectric constant. Gamma spectral logging systems have been used for many years to partition natural gamma activity into components attributed to the three natural radioisotopes (U, Th, and K), and to manmade isotopes such as Co and Cs (Lock and Hoyer, 1976). However, much better spectral resolution is given by recently developed gamma spectral systems operated downhole at cryogenic temperatures. The latest geochemical probes being developed include pulsed neutron generators for activation in conjunction with gamma spectral probes. Only limited results from these advanced geochemical probes have been published, but preliminary results indicate that these logs can distinguish proportions of clay minerals such as illite, smectite, and kaolinite from feldspars, quartz, and other heavy minerals (Herron, 1986).

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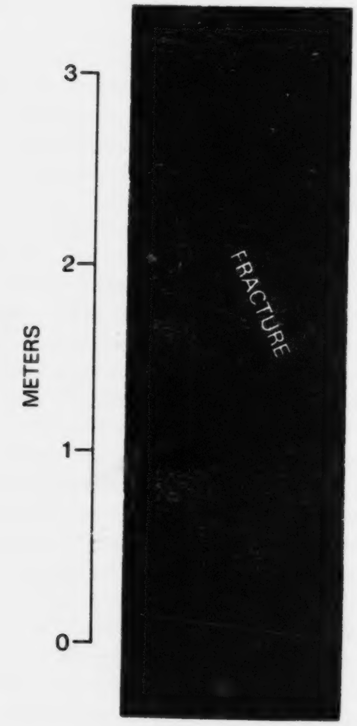

Figure 76. Well defined televiewer log of high-angle fracture in shale.

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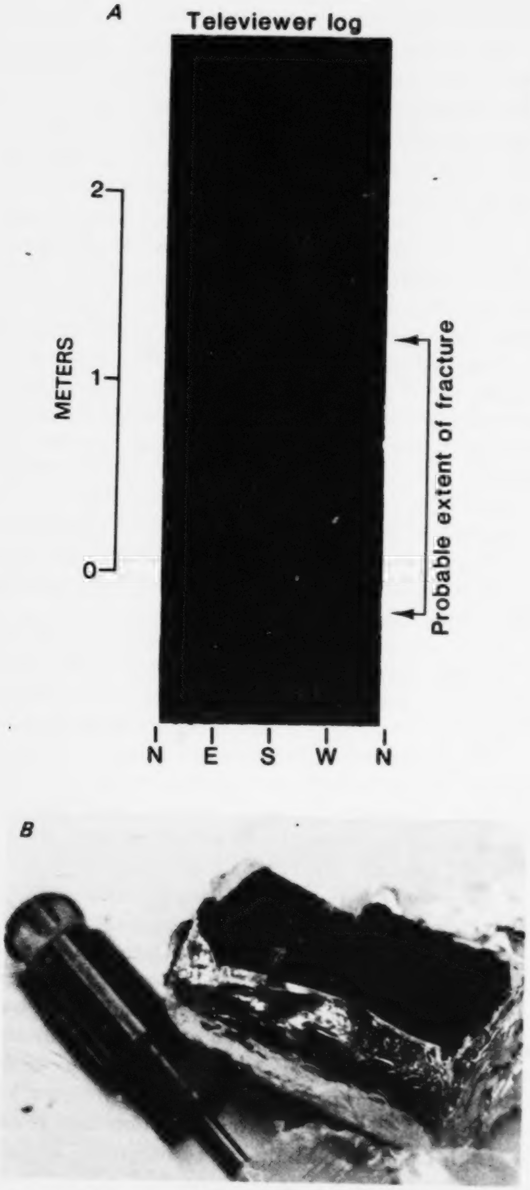

Figure 77. *A*, Televiewer log showing fracture. Probable location of fracture in borehole wall; and *B*, Core sample of shale showing fracture (adapted from Paillet and others, 1985).

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Surface Geophysical Methods Applicable to Characterization of Low-Level Radioactive-Waste Sites

By Gary R. Olhoeft

Continuous, noninvasive investigation of the physical and chemical properties of the Earth in three dimensions can be accomplished by using surface geophysical techniques. Drilling produces highly quantitative information versus depth at very localized spots. However, drilling is expensive, increases the hazard for spread of contaminants, and may miss the target; the drilling process affects the subsurface environment. Surface geophysics is most valuable in characterizing the overall heterogeneity of a site, locating the spots to drill, and providing "context" for the drill information. It is particularly valuable for finding out whether the drill hole was spotted in a normal or an anomalous location (Benson and others, 1984; Walther and others, 1988; Wynn and Roseboom, 1987). In context, the results of the drilling may be used to refine the geophysics calibration.

Site characterization by geophysics includes maps of areal and depth location of water-table topography, permeability barriers, lithological and stratigraphic boundaries, fractures and faults, bedrock subsurface topography, subsidence cavities, buried stream channels, ground-water quality, and other hydrogeological features. Geophysical methods also can be used to locate buried pipes, cables, trenches, barrels, concrete walls, slurry barriers, and other site features created by the activities of man (Romig, 1986).

This hydrogeological and cultural information is useful in modeling the site to infer or predict the migration, mitigation, and eventual fate of contaminants. By repeating geophysical surveys, measurements of changes over time at a site may monitor the performance of a site in isolating the waste. Geophysical techniques also can monitor active processes and enable one to infer information not otherwise directly measurable. Ground-penetrating radar was used to monitor the lateral variability in vertical transmissivity from the migration of the wetting front downwards. Radar and resistivity also were used to monitor the movement of ground water through fault zones.

Geophysical techniques also can sometimes directly detect and map the migration of contaminants and their interaction with soil. Conventional resistivity or electromagnetic induction conductivity mapping can detect inorganic contaminants. Complex resistivity can locate organic contaminants by measuring clay-organic reactions. Some organic reactions with clay significantly alter the hydraulic conductivity of clay barriers, increasing their permeability (Olhoeft, 1988).

Geophysical methods also can be used to get information about variation with scale as well as lateral and depth extent. Scale dependence is obtained by measurements of petrophysical parameters on core in the laboratory at centimeter scale, with borehole geophysics at meter scales, with hole-to-hole and hole-to-surface geophysics at tens to hundreds of meters scales, and with airborne or satellite geophysics at scales of kilometers.

Geophysical techniques do not always work. Ground-penetrating radar works better than seismic techniques in loose, sandy soil. Shear-wave seismic techniques work better than radar or seismic compressional-wave techniques in clay soil (Hasbrouck, 1987). Complex resistivity is the best method to use to map active chemical processes, but it is ineffective at sites with many utilities and metal fences. Electromagnetic conductivity is the effective way to map inorganic contaminants, but it misses organic contaminants. To investigate and characterize a site geophysically, several different geophysical techniques may be required. Owing to different site conditions of hydrology, geology, or culture, and to the nature of the problem to be investigated, some techniques may not work at all, whereas others may work well.

The interpretation of geophysical data also requires extensive computer modeling to remove the effects of surface topography and nearby cultural features and to interpret the geophysical parameters of resistivity, velocity, and others into more useful site parameters, such as water content and salinity, porosity, permeability, and so forth. Such modeling also identifies the uniqueness of the solution derived by geophysics and the impact of site design features on future monitoring with geophysics.

Geophysical methods are never used in isolation. They should be the first step taken toward an integrated site characterization. Geophysical methods are used to guide the location of drill holes, to interpolate between drill holes, to yield information where it is impractical or hazardous to drill, to measure variations in properties and site homogeneity on scales not reachable by drilling, and to monitor active processes or changes with time. It is unlikely that sites will ever be truly "simple" in the near-surface environment, so all the tools available to characterize a site should be used.

Most geophysical techniques were developed for seismic petroleum exploration at depths greater than several hundred meters. Less than 5 percent of the free world's geophysicists are trained in the techniques of geophysical exploration in the top 100 m of the Earth.

Most geophysicists also are classically trained in only one or a few techniques. To solve site characterization and monitoring problems effectively requires broad experience with many geophysical techniques along with computer modeling and interpretation skills. Geophysicists must be knowledgeable enough to discuss and translate the results of their investigations into terms meaningful for the hydrologist, geologist, design engineer, lawyer, and layman.

Though there are many problems, state-of-the-art geophysics has the ability to characterize low-level radioactive-waste sites (Beers and Morey, 1981; Daniels, 1983; Davis and others, 1984; Horton and others, 1981, 1982; Olsson and others, 1984; Watts, 1983). Such characterization can be done with fractional meter accuracy over volumes of ground hundreds of meters on a side and tens of meters deep. If gathered in advance, the geophysical information can provide an optimum drilling plan to acquire more detailed and quantitative site calibration and characterization. If the requirements and interferences of geophysics are properly built into the design of low-level waste sites, geophysics also can provide an effective program for long-term performance monitoring of the site.

Very few geophysical studies have been done at existing low-level radioactive-waste sites (Wynn and Roseboom, 1987). At some sites, this is because site design or cultural features provide too many interferences, and in others because "it was tried once and didn't work." Nothing works all the time. Sometimes, the studies are not effective because the operator or interpreter didn't know his job. If appropriately applied, much useful information may be derived from geophysical surveys at both existing and future sites.

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Regional Screening and Selection of Candidate Sites for California's Low-Level Radioactive-Waste Disposal Facility

By Greg Hamer *and* Eric G. Lappala

Introduction

California law, Senate bill 342 of 1983, requires that a low-level radioactive-waste disposal facility be established in California. The facility is required to meet the responsibilities of the State under the Federal Low-Level Radioactive-Waste Policy Act as amended in 1985 (Public law 99–240) for the safe disposal of low-level radioactive waste generated within the State by non-Federal activities.

Criteria development for the location of a technically suitable site in California began with a study by the California Department of Health Services (DHS) in 1982. The study identified several criteria for site location, including those related to land use, population, access, economic impact, geology, and hydrology. Geologic and hydrologic criteria included:

1. Exclusion of areas of more than 25 cm average annual rainfall;
2. exclusion of active fault zones;
3. avoidance of areas with recent volcanic activity;
4. exclusion of wetland, coastal high-hazard, or 100-year flood-plain areas;
5. exclusion of contact between waste and ground water; and
6. avoidance of economic mineral resource areas where exploitation of resources would impair site performance.

Using those criteria that were regionally applicable, California DHS screened the State and developed an initial set of maps indicating parts of the State that might contain suitable sites.

Of the regionally applied California DHS criteria, the most important in regard to technical suitability was the requirement that mean annual rainfall be less than 25 cm. Areas of less than 25 cm mean annual rainfall exhibit many of the necessary characteristics that satisfy the technical requirements and performance objectives associated with facility siting. Flooding, ponding, onsite springs and seeps, and large water-table fluctuations (all of which are to be avoided) occur with far less frequency in arid climates. Because water movement in both unsaturated and saturated zones is the primary mechanism for migration of waste from a disposal site, arid areas that limit the potential for contact between the waste and water are considered optimal for siting.

The criteria for further screening of candidate areas were formulated by extending the California DHS criteria to include Federal requirements as given in 10 CFR 61 (U.S. Nuclear Regulatory Commission, 1982). Federal requirements state that a disposal site must be capable of being sufficiently characterized, analyzed, modeled, and monitored to enable confident prediction of the fate and expected environmental concentrations of any nuclides that may be released from the site. U.S. Ecology, Inc. (1987) and HLA (Harding Lawson Associates) formulated a conceptual model of the "ideal" site that would come the closest to meeting the extended criteria of the California DHS and 10 CFR 61. The application of this conceptual model to the potentially suitable areas identified by California to further delineate candidate site areas is described in this report.

Conceptual Model Development

The conceptual framework for screening was based on both the State and Federal regulations requiring that the natural attributes of a prospective site allow full characterization, modeling, monitoring, and analysis of geologic, meteorologic, hydrologic, and radiologic factors. Geologically and hydrologically simple sites are more likely to meet the conditions for characterization, modeling, monitoring, and analysis than more complex sites. Therefore, the attributes that qualify a site as simple for the purposes of establishing a consistent screening model were reviewed. These attributes are discussed in the following sections.

Ground-water conditions are less complex when:

1. Ground-water recharge and discharge areas and processes at the site and vicinity can be well defined.
2. Ground water occurs in geologic material having uniform interstitial, primary porosity and permeability, where its movement is more predictable and easier to characterize. In rocks characterized by secondary porosity, that is, fractures and solu-

tion cavities, ground-water flow is more difficult to characterize because of the degree of heterogeneity and anisotropy. Fractures and solution channels increase the uncertainty in predictive modeling of possible ground-water transport (Freeze and Cherry, 1979, p. 30–36, 409; University of Arizona, 1980, p. 1).

3. The three-dimensional direction(s) of ground-water movement is (are) relatively easy to establish, and flow is least affected by the presence of subsurface barriers (for example, faults) or numerous withdrawal points (for example, wells or well fields).
4. The ground-water system is in a state of dynamic equilibrium; for example, ground water is not influenced by large withdrawals or highly irregular recharge events that could result in large water-level changes.
5. Surface ground-water discharge, such as springs and seeps, does not occur.

Surface-water conditions are less complex in the following instances:

1. Upstream drainage areas are relatively small and well defined.
2. The terminus of surface-water flows is well defined.

Geologically simple sites have the following general characteristics:

1. Geologic conditions are relatively stable (as characterized by minor seismic activity), and there is no evidence of historic or recent fault activity.
2. Geologic units containing ground water are not fractured, warped, or folded.
3. Subsidence does not occur.
4. There is a low probability of volcanism occurring within the 500-year regulatory timeframe for the wastes.

Specific components of the regional screening model were developed by considering the various types of geologic and hydrologic environments that would incorporate the above characteristics to the greatest degree. Figure 78 presents a block diagram and cross-sectional view of the type of area that best suits the conceptual screening model.

Topographically closed basins were chosen as a key feature of the screening model. Such basins provide locations where hydrologic and geologic conditions are likely to be less complex than in large, regionally extensive or open drainage systems. In a topographically closed basin, any potential transport of contaminants from a site via surface or subsurface pathways (for example, surface runoff or ground-water flow) will more than likely be easier to define.

The terminus of any surface-water flow or runoff is easily identified if adequate topographic control within a basin is provided. In most basins, surface water terminates in a playa or dry lakebed where it may pond periodically. The ability to define the limits of a surface-water system within a basin increases the likelihood that a potential site will meet performance objectives.

Research at the low-level radioactive-waste disposal site near Beatty, Nev., by the U.S. Geological Survey (Nichols, 1986) and other studies by the Harding Lawson Associates (1986) indicate that recharge to the water table is extremely low in some areas of desert basins with deep ground-water tables. For example, the long-term deep percolation rate at the Beatty, Nev., disposal site was estimated to be approximately 4 cm every 1,000 years (Nichols, 1986). The lack of significant deep percolation is the result of low rainfall (typically less than 25 cm/yr) and high evaporation (generally more than 250 cm/yr in desert areas. In the arid desert environment, rainfall percolates a relatively short distance into the ground before it is absorbed by capillary forces that "wet" the dry moisture-deficient soils. The downward movement of the moisture that does percolate is countered by evaporative drying and plant transpiration at or near the soil surface. Within topographically closed basins, the areas where recharge is unlikely to occur are bajada or alluvial plain surfaces that are remote from the upper parts of alluvial fans (fig. 78*B*). Although the potential for recharge is low in desert basins, certain parts of those basins have a higher probability of receiving recharge. Significant recharge can occur in upper parts of alluvial fans and major washes where precipitation runoff is concentrated.

The likelihood that ground-water flow terminates within a topographically closed basin also is high. In many closed basins, ground water flows from the margins of the basin toward the basin center where it is discharged as evaporation or transpiration (fig. 78). In such basins, the ground-water system is more easily characterized, modeled, and analyzed because recharge and discharge points can be more readily defined.

In basins where there is known subsurface ground-water outflow, the outflow area may be readily identifiable (where it occurs through an alluvial gap or pass between valleys).

Porous Geologic Material

Site areas that have subsurface movement of water (and potential transport of any contaminants) in the unsaturated and saturated zones occurring in primary porosity associated with porous, nonindurated geologic materials (for example, alluvial sediments) were considered to be more easily characterized than those sites where movement occurs via secondary permeability associated with fractures and solution openings in indurated rocks. Areas of indurated rock therefore were excluded.

Ground-Water Depth

For the screening process, a limit of 30 m was chosen for the minimum depth to ground water. Placing arbitrary but realistic limits on the depth to ground water enabled the model to meet the following siting requirements:

1. The disposal site should not be located in wetlands;
2. wastes should not come in contact with ground water;
3. there should be sufficient distance between the waste and the underlying ground water to allow for early detection of any leakage before it could contact the ground water; and
4. there should be no discharge of ground water by springs or seeps.

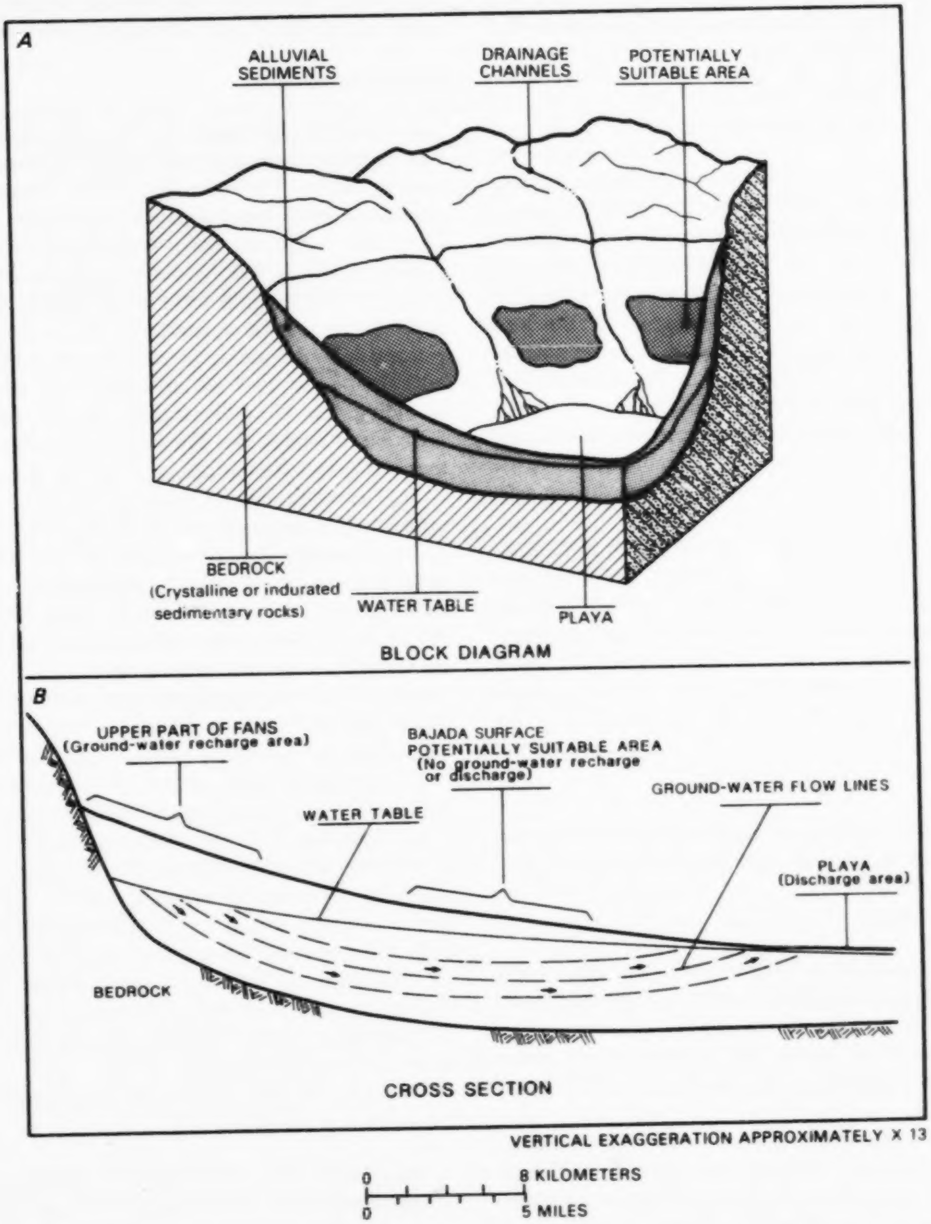
A
ALLUVIAL SEDIMENTS
DRAINAGE CHANNELS
POTENTIALLY SUITABLE AREA
BEDROCK (Crystalline or indurated sedimentary rocks)
WATER TABLE
PLAYA
BLOCK DIAGRAM
B
UPPER PART OF FANS (Ground-water recharge area)
BAJADA SURFACE POTENTIALLY SUITABLE AREA (No ground-water recharge or discharge)
GROUND-WATER FLOW LINES
WATER TABLE
PLAYA (Discharge area)
BEDROCK
CROSS SECTION
VERTICAL EXAGGERATION APPROXIMATELY × 13
0
8 KILOMETERS
0
5 MILES

Figure 78. Type of geologic and hydrologic area that has optimum characteristics to fit conceptual model of a safe low-level radioactive-waste disposal facility. *A*, Block diagram of a topographically closed basin showing relations of geologic and hydrologic features; *B*, Cross section showing hydrologic conditions. Arrows indicate direction of ground-water flow.

If it is assumed that wastes can be buried as deep as 15 m, the criterion of 30-m depth to ground water allows for a minimum 15 m of unsaturated zone between the waste and the water table. The waste is unlikely to come in contact with ground water because water-table fluctuations in arid areas that are not greatly influenced by pumping or artificial recharge are not likely to fluctuate as much as 15 m.

Quality of ground water was not considered as the basis for exclusion of a particular area in regional screening.

Faulting

For conceptual model development and screening, major active and potentially active faults were avoided. Faults considered active are those with known historical activity (last 200 years) and potentially active faults are those that show evidence of movement during Quaternary time (last 2 million years). Jennings (1975) divided major faults in California into categories on the basis of the evidence for their activity. He includes categories for historically active and Quaternary age faults. Minimum setbacks of 0.5 mi from the mapped trace and 2 mi along the projected trace of a fault were established to avoid areas potentially subject to ground rupture during seismic activity.

As indicated in Subpart D, 61.50(a)(10) 10 CFR 61 (U.S. Nuclear Regulatory Commission, 1982) and the California DHS criteria, areas where surface geologic processes may impair the site's ability to meet performance objectives should be avoided. One of the most important surface processes that could affect the site is the presence of unstable soils. In the model used for screening, this consideration was included by exclusion of areas with unstable soils including:

1. Areas on or in the path of large landslides or slumps,
2. eolian (wind-deposited) sand deposits or sand dune deposits, and
3. subsidence areas.

A buffer zone of 1.6 km around sand dunes was designated to allow for potential shifts or migration of the dunes. In areas where the eolian surficial sediments were present, but in which topographic expression of eolian features was not evident, a buffer zone was not designated.

For regional screening, areas near known volcanoes or recent volcanic activity were excluded. This is consistent with both Federal (Nuclear Regulatory Commission, Subpart D, 61.50(a)(9), 1981) and California DHS siting criteria. The zone excluded was a minimum of 8 km from a Recent-age volcano or cinder cone. The minimum buffer zones were used on a regional basis considering that for specific areas the nature of the volcanic deposits, their age, location, and relationship to surrounding features would require further evaluation.

As indicated in State and Federal regulations, surface-water conditions are important criteria in site selection. The screening model excluded flood-prone areas that could be identified regionally, such as dry lakebeds and major regional riverbeds and washes.

Exclusion of areas based on more localized conditions, such as smaller washes and drainage areas was reserved for small-area site-specific screening.

Criteria Application

Criteria developed for the screening model first were applied on a regional scale and then on an area-specific scale. The screening scale determined when specific criteria were applicable. Criteria applied on a Statewide (regional) basis included rainfall and topographic basin closure. Within topographically closed basins, the remaining criteria were applied and included depth to ground water, rock type, faulting, unstable soils, volcanism, and flooding. Screening was performed using both published and unpublished data from agencies, including the U.S. Geological Survey, the California Division of Mines and Geology, the California Department of Water Resources, and various private sources.

The result of the screening was the identification of numerous geologically and hydrologically suitable sites. Three candidate sites were selected, each 260 ha in size, located in the Ward and Silurian Valleys of San Bernardino County and in the Panamint Valley of Inyo County. All sites met the geologic and hydrologic regional screening criteria and various other land-use and environmental criteria. The three candidate sites also received strong public support from a Citizen's Advisory Committee established as part of the overall siting study.

During the latter half of 1987, detailed site characterization studies were begun. The purpose of the studies is to determine if the three sites are technically suitable, to provide necessary information to compare the three candidate sites, and to select a preferred site. The preferred site then would be characterized, analyzed, modeled, and monitored as required for licensing by the State of California. If, in the characterization studies, any characteristics are identified that disqualify the site, such as faulting or shallow bedrock, the site will be removed from further consideration.

Characterization activities to be performed at the candidate sites include:

1. Installation and monitoring of a meteorologic station.
2. Installation and monitoring of wells, including several screened near the water table and several deeper wells.
3. Installation and monitoring of a series of thermocouple psychrometers and tensiometers in the upper 10 m of soil.

4. Drilling and sampling of soil for geotechnical and geochemical testing including soil strength characteristics and physical and chemical classification.
5. Performing infiltration and aquifer tests.

Field data will be analyzed and used as input for geochemical modeling, unsaturated zone modeling, ground-water flow, and transport modeling. Model results will be used to perform dose assessment analysis to meet licensing requirements.

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